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McGarry et al.

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[45] **Date of Patent:** **Jan. 19, 1999**

[54] **IMAGE FORMATION APPARATUS FOR VIEWING INDICIA ON A PLANAR SPECULAR SUBSTRATE**

5,231,536 7/1993 Wilt 250/237
5,386,481 1/1995 Hine et al. .
5,469,294 11/1995 Wilt 359/436

[76] Inventors: **E. John McGarry**, 14534 SW. Pinot, Portland, Oreg. 97224; **Jeffrey Friedman**, 3320 S. Shore Blvd., Lake Oswego, Oreg. 97034

Primary Examiner—Howard Britton
Attorney, Agent, or Firm—Russ Weinzimmer

[21] Appl. No.: **954,983**
[22] Filed: **Oct. 21, 1997**

[57] **ABSTRACT**

Related U.S. Application Data

[63] Continuation of Ser. No. 630,421, Apr. 2, 1996, abandoned.
[51] **Int. Cl.**⁶ **H04N 7/18**
[52] **U.S. Cl.** **348/87; 348/131; 382/145**
[58] **Field of Search** 348/87, 92, 126, 348/128, 131; 382/145; H04N 7/18

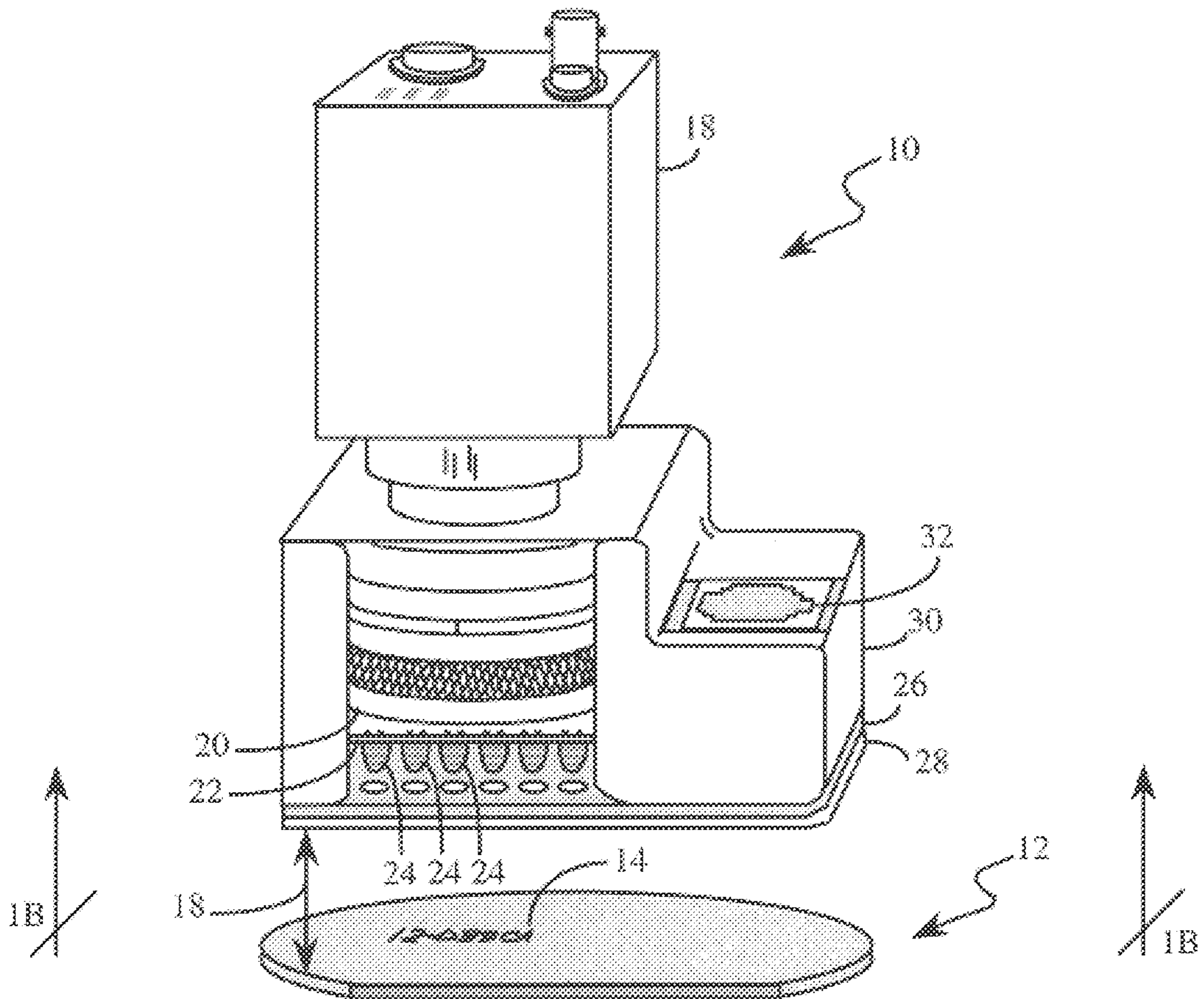
The image formation system of the invention provides a compact apparatus for viewing indicia on a planar mirror-like (specular) substrate, such as a semiconductor wafer. The invention is particularly effective in viewing indicia that require either brightfield or high-angle darkfield illumination. These and other benefits of the invention are provided in part by providing selective directional focusing and defocusing of the reflected image of the illumination elements that illuminate the indicia, while providing substantial focusing of the image of the indicia at high contrast. In the case of high-angle darkfield illumination, directionally selective focusing maximizes useful darkfield area by minimizing interference between the reflected image of the illumination sources and the image of the indicia, while the contrast of the image of the indicia is maximized.

[56] **References Cited**

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38 Claims, 18 Drawing Sheets



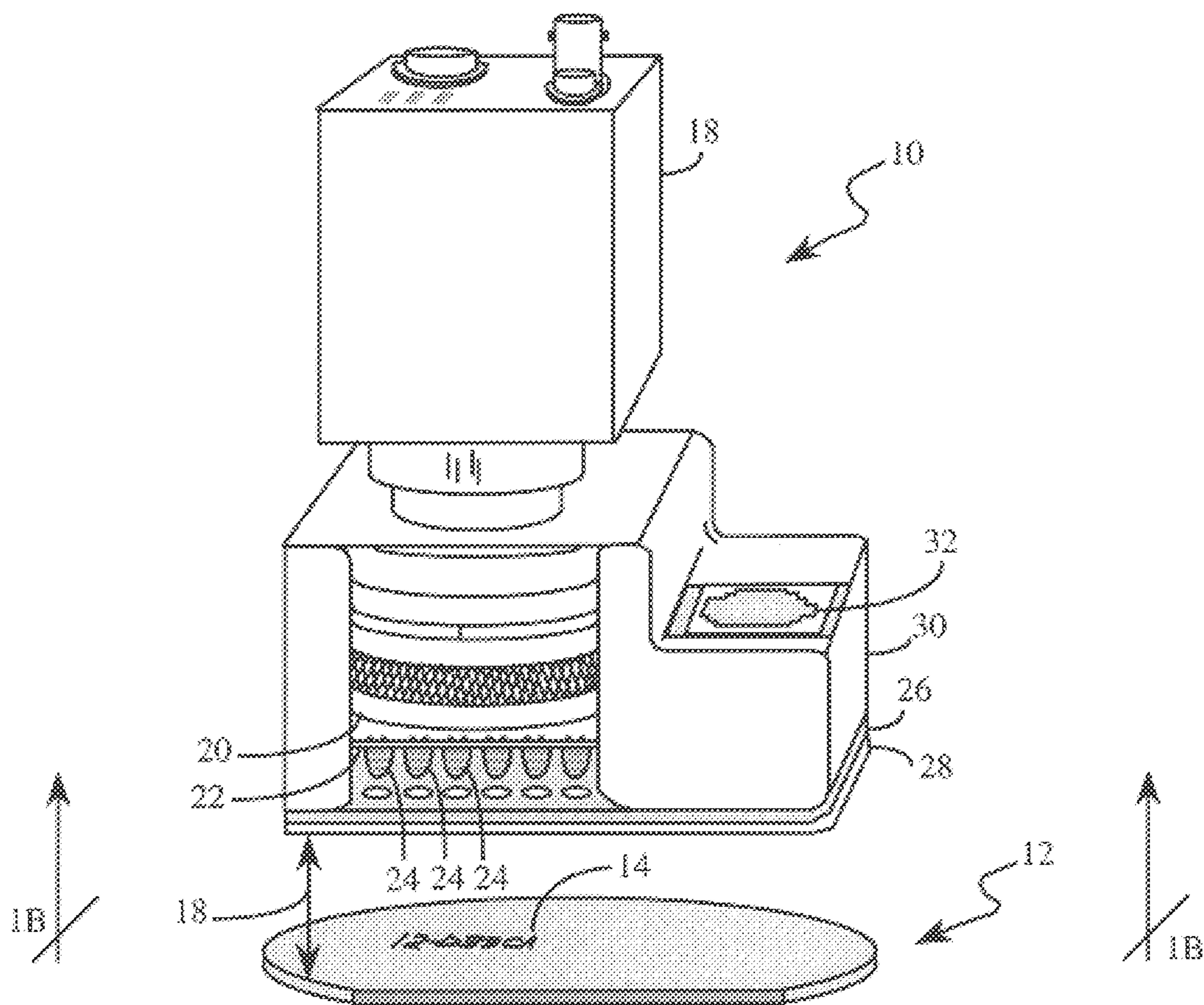


FIG. 1A

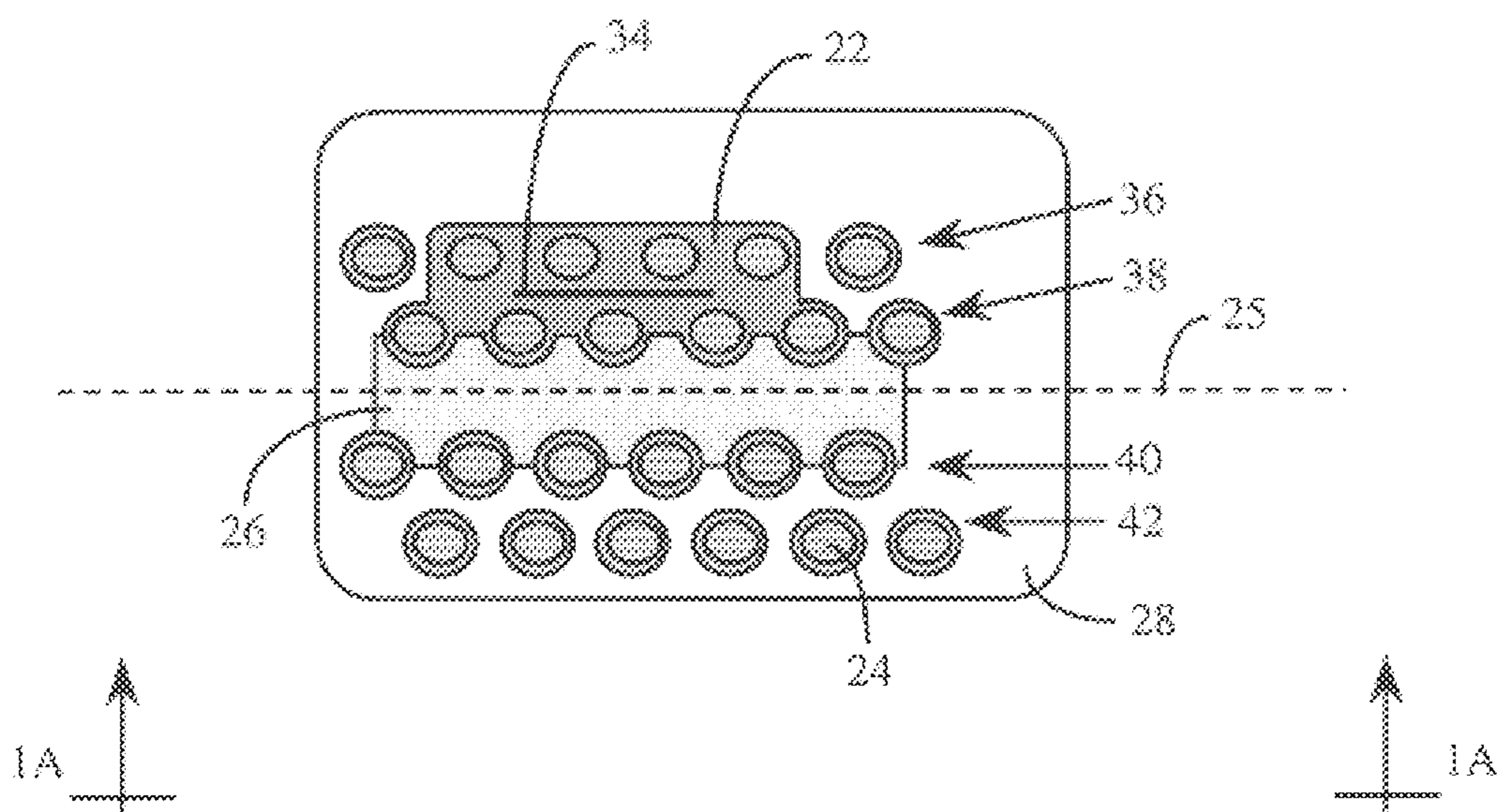


FIG. 1B

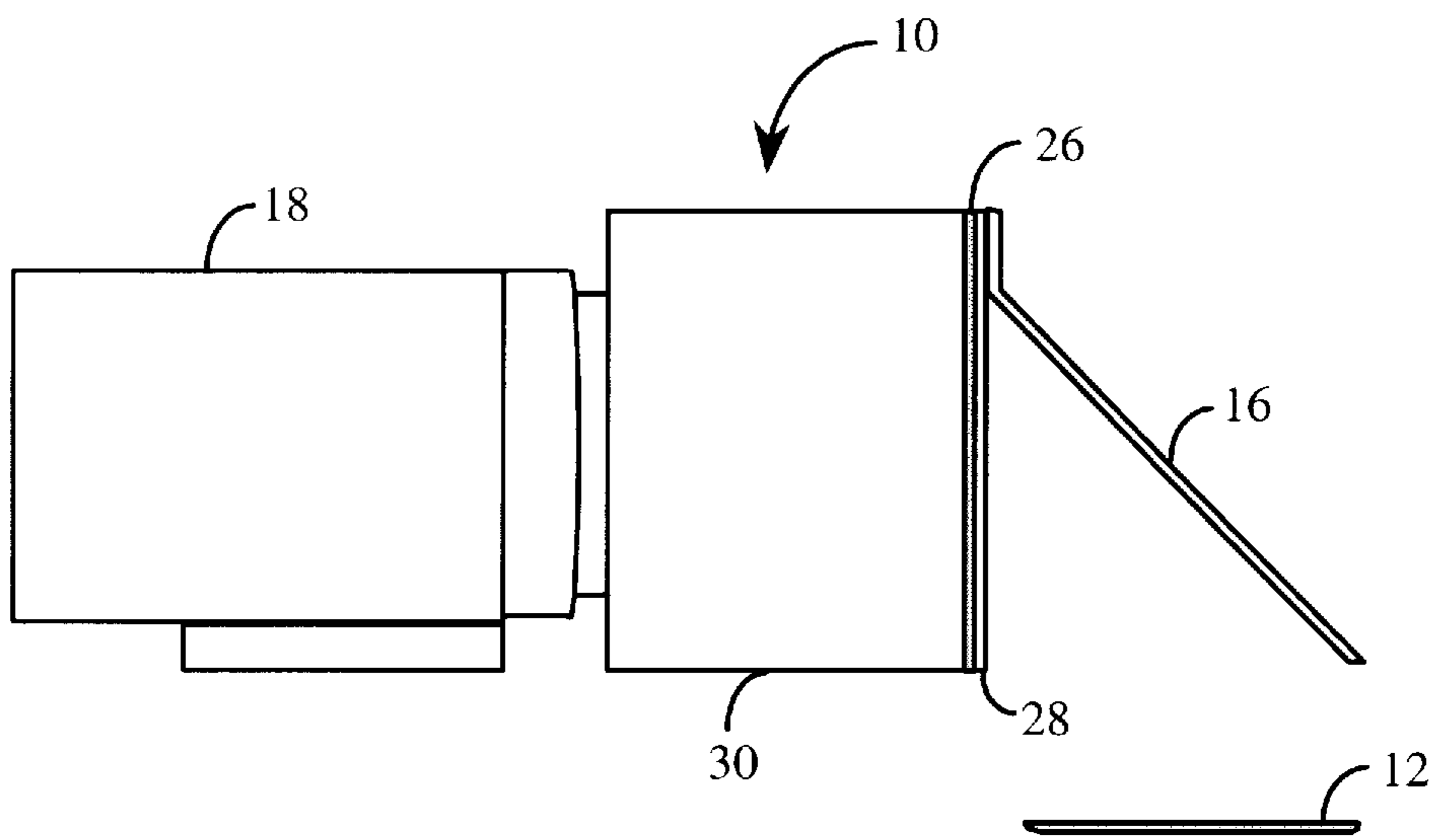


FIG. 1C

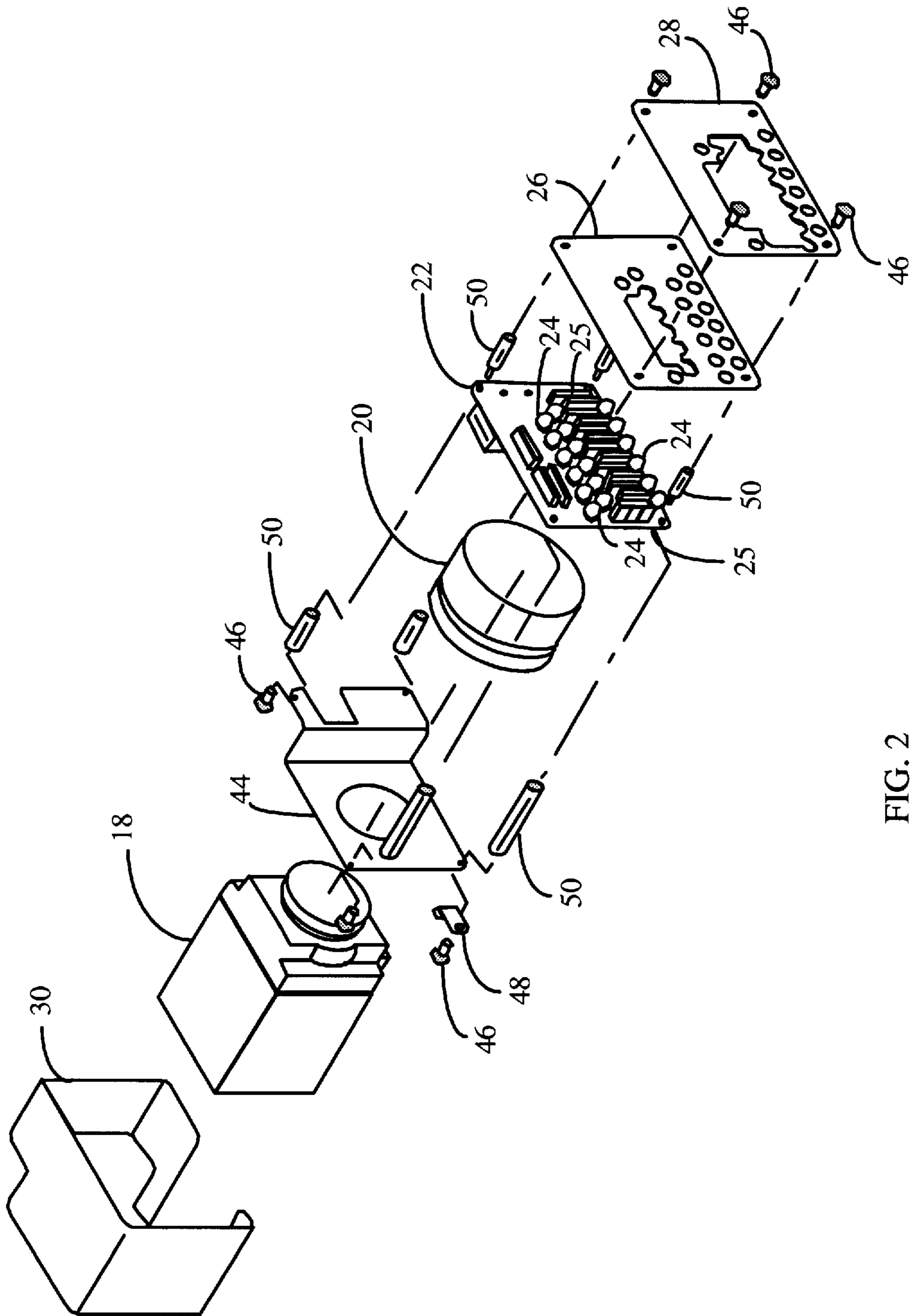


FIG. 2

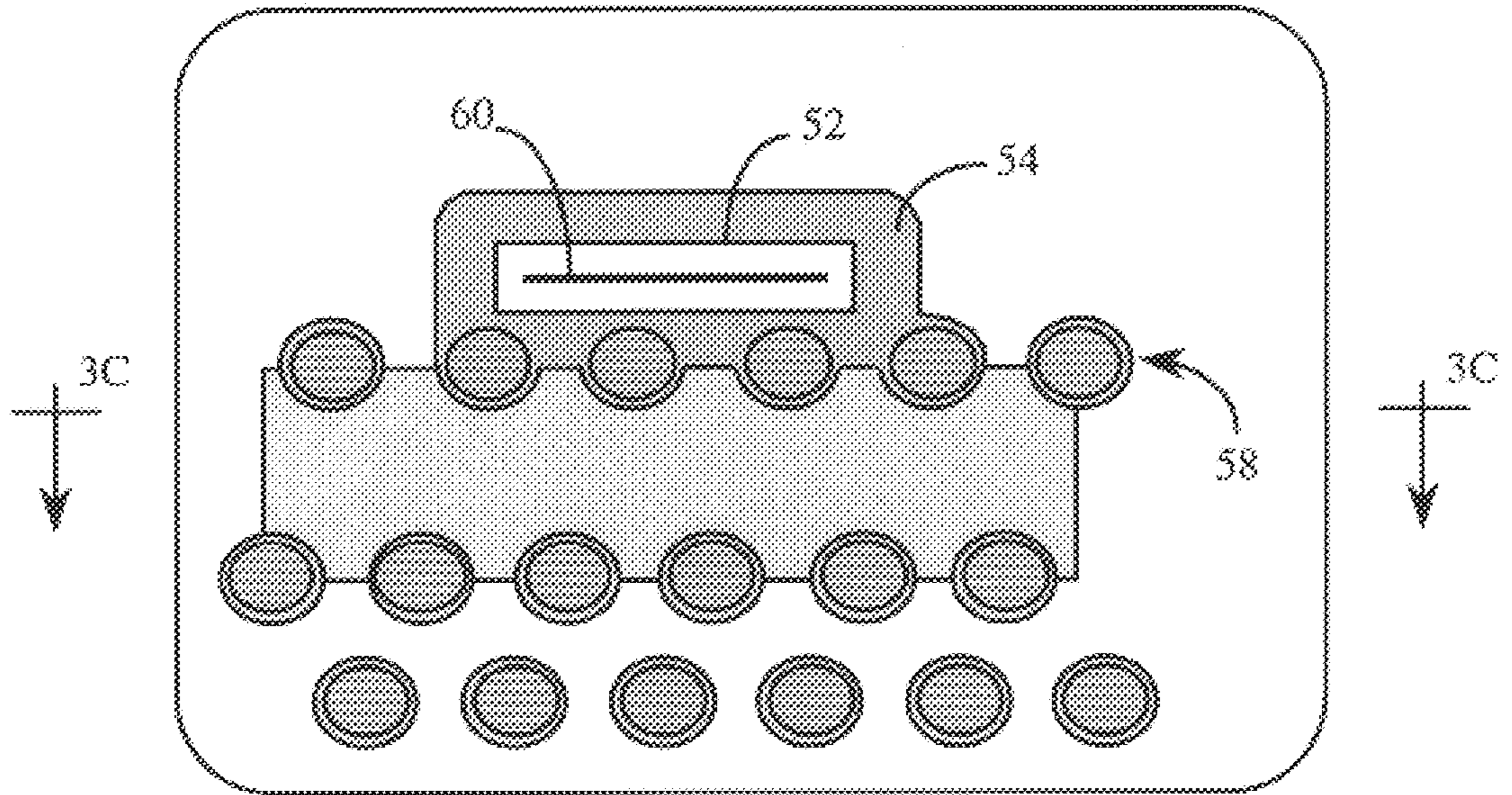


FIG. 3A

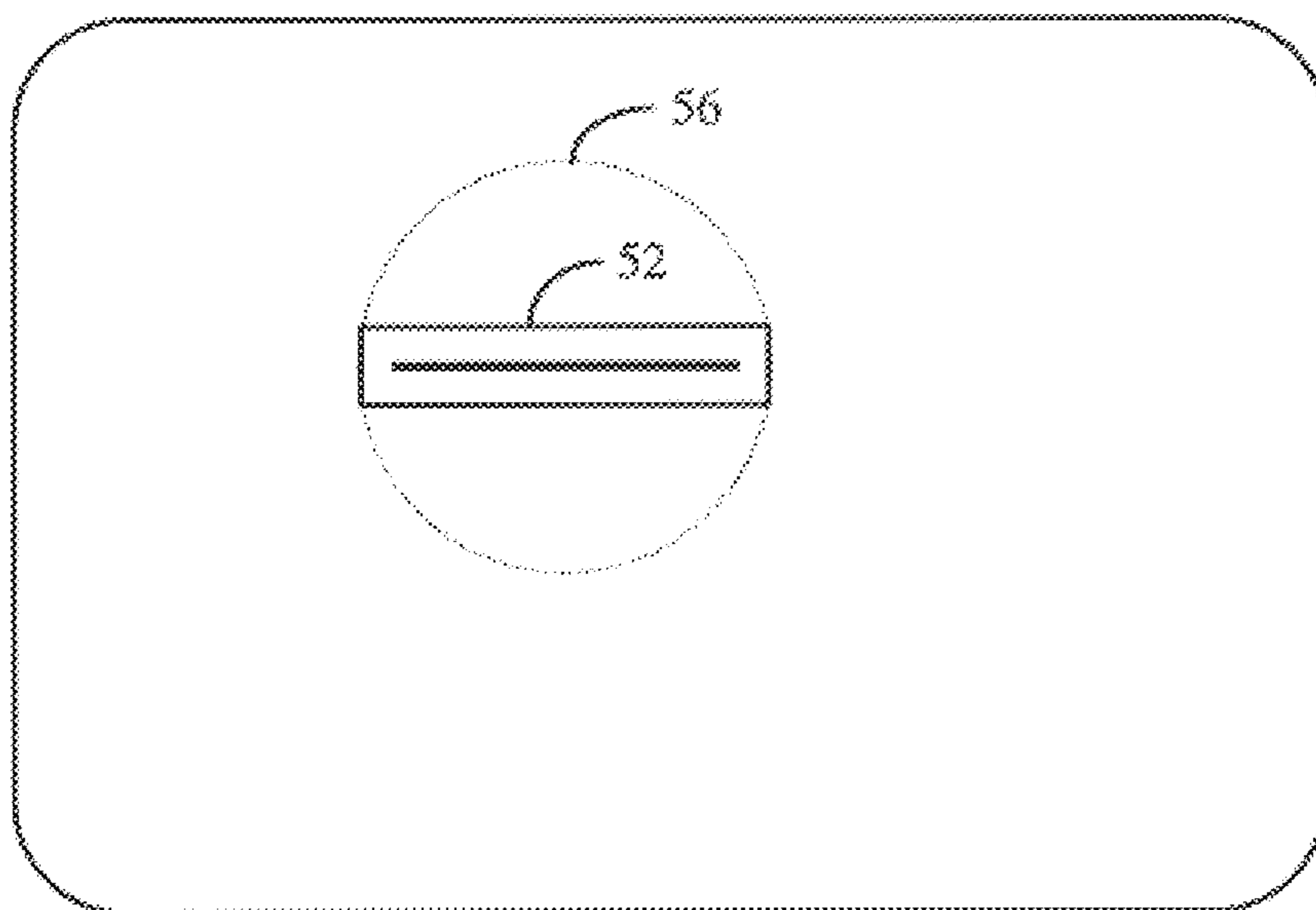


FIG. 3B

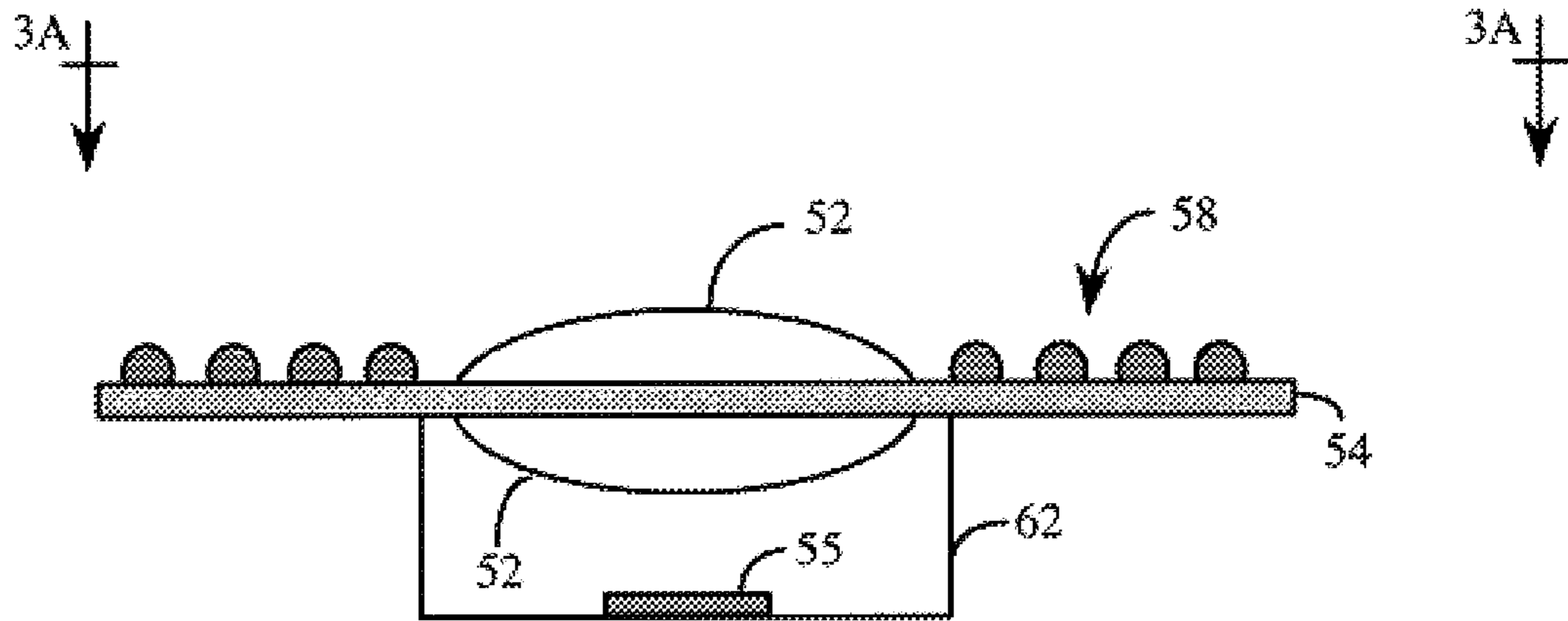


FIG. 3C

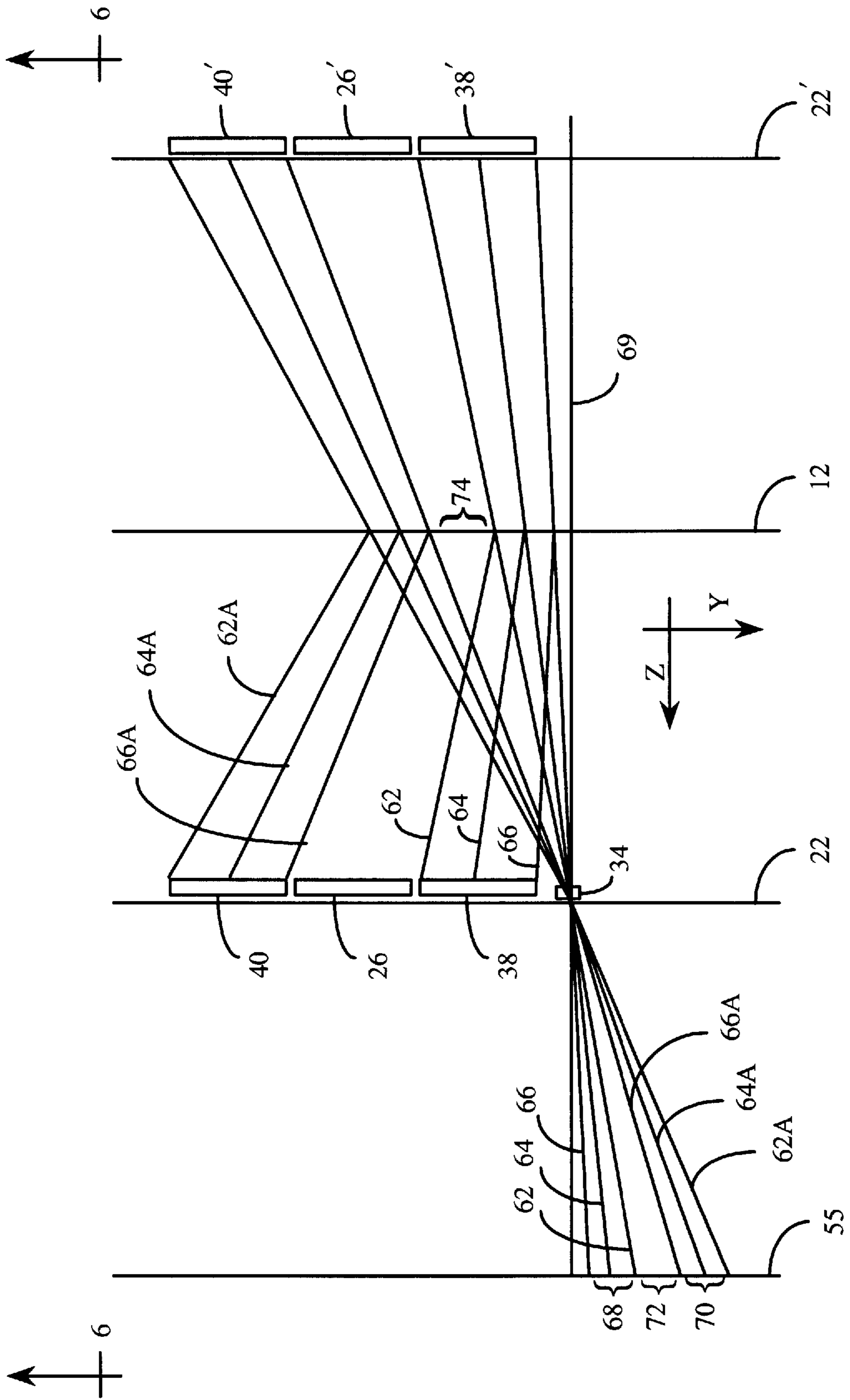


FIG. 4

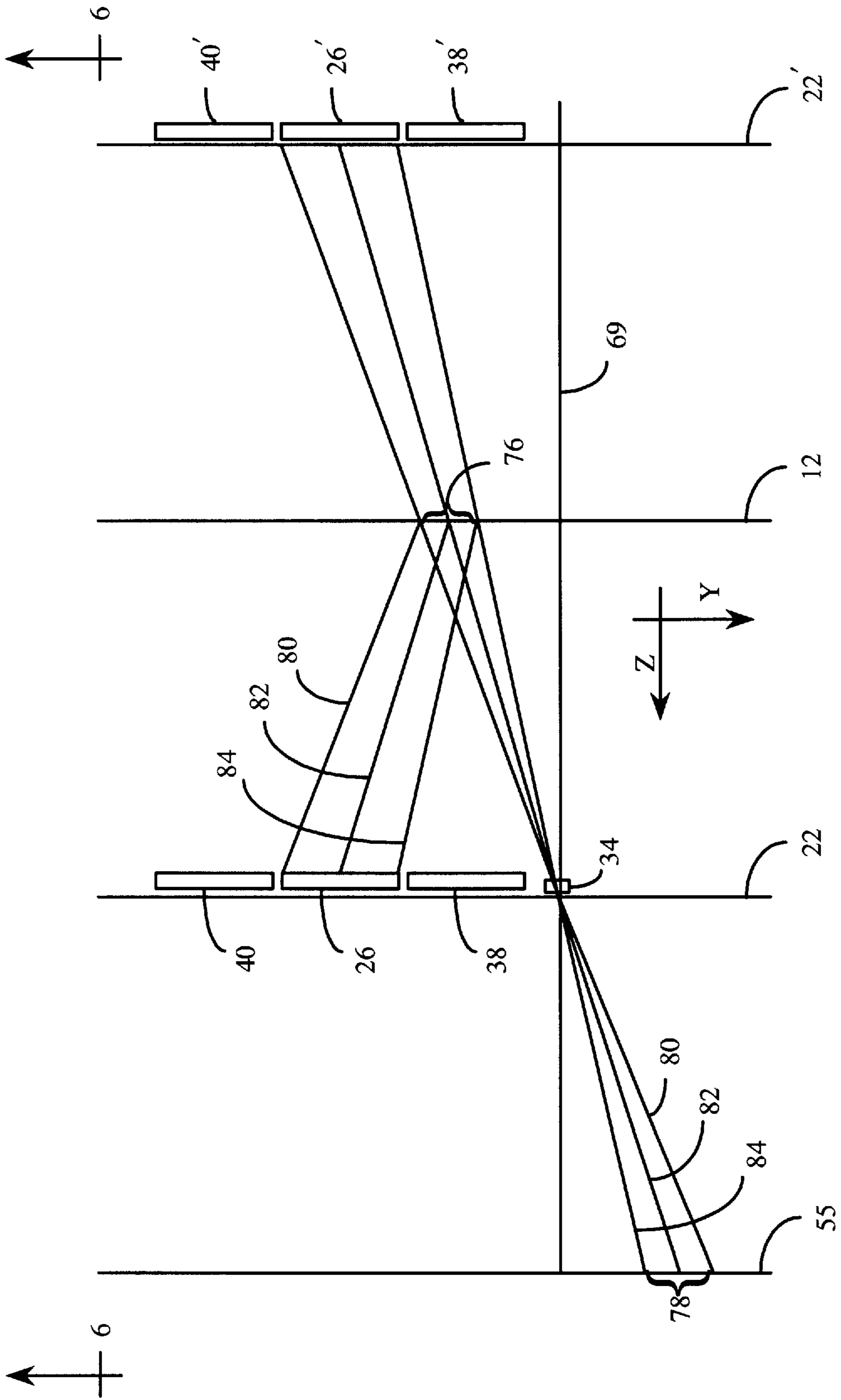


FIG. 5

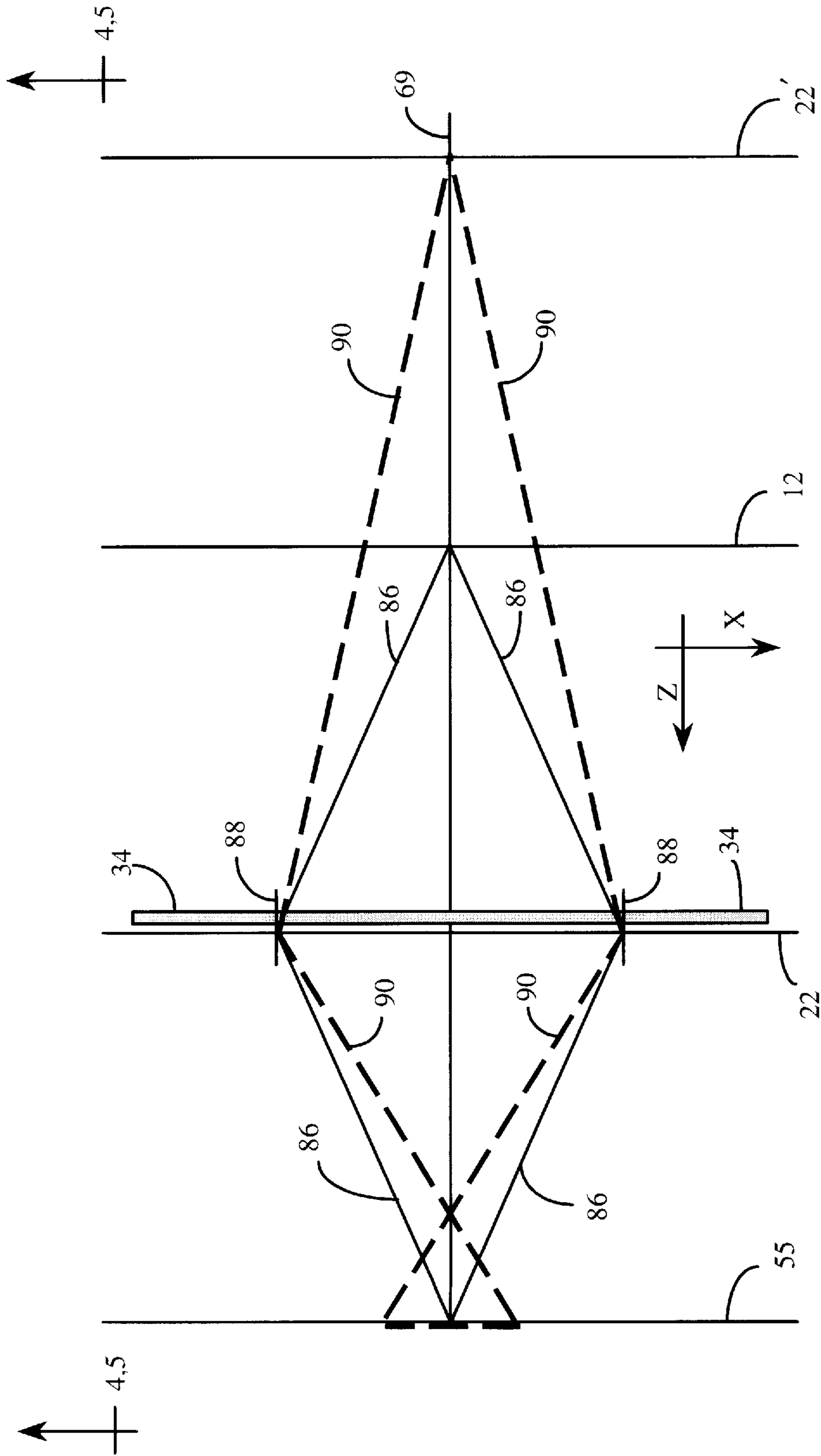


FIG. 6

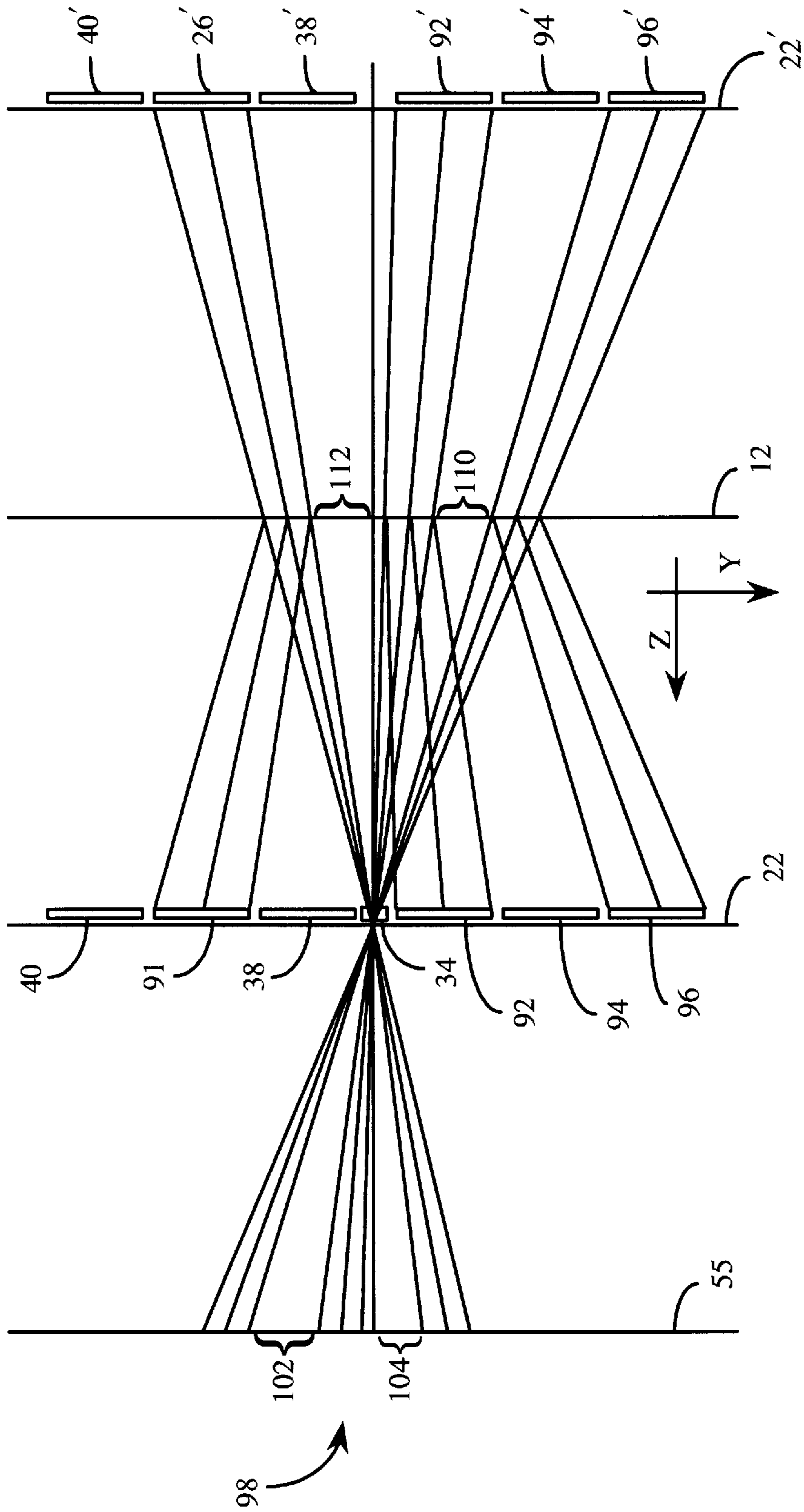


FIG. 7

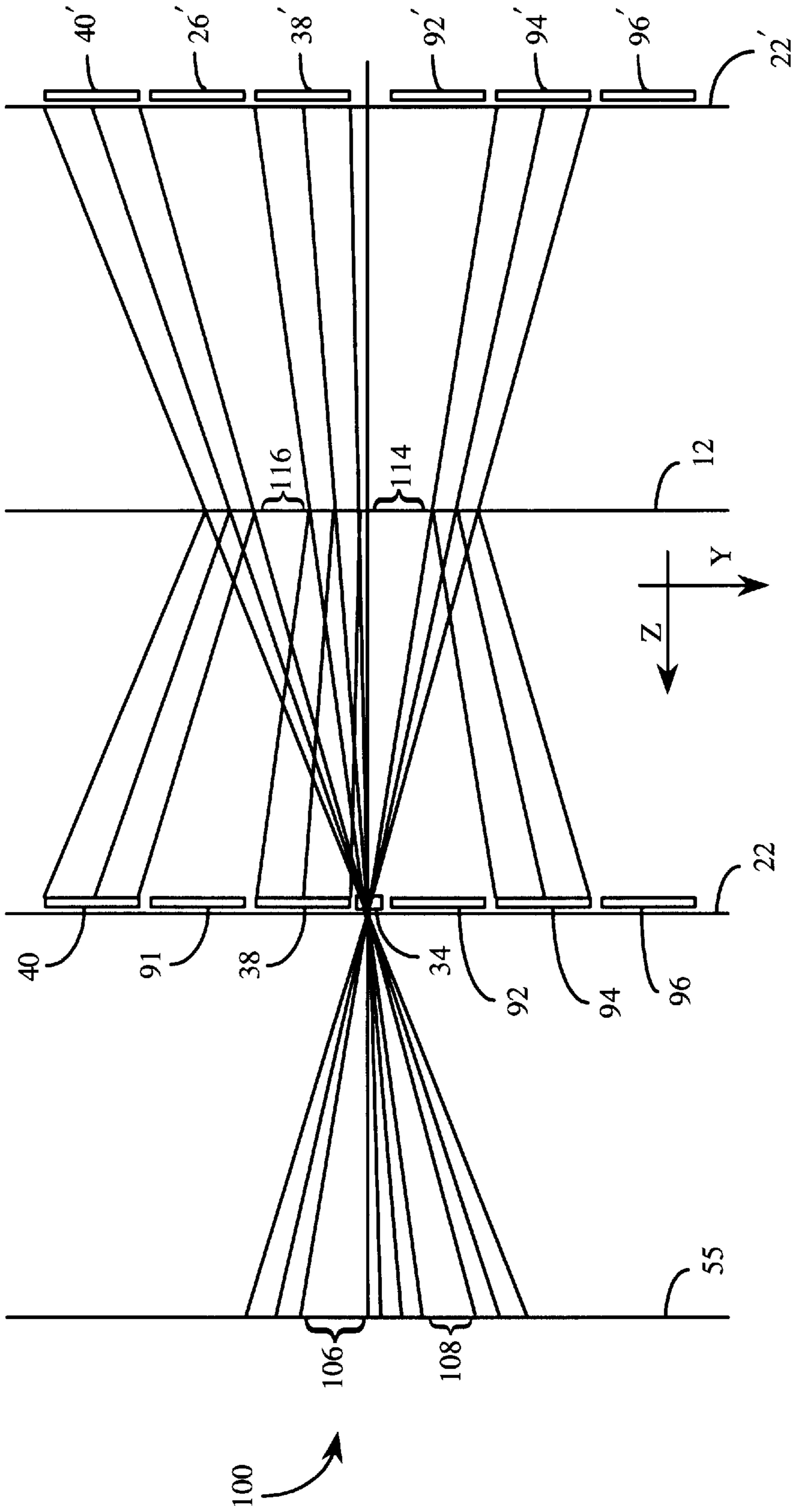


FIG. 8

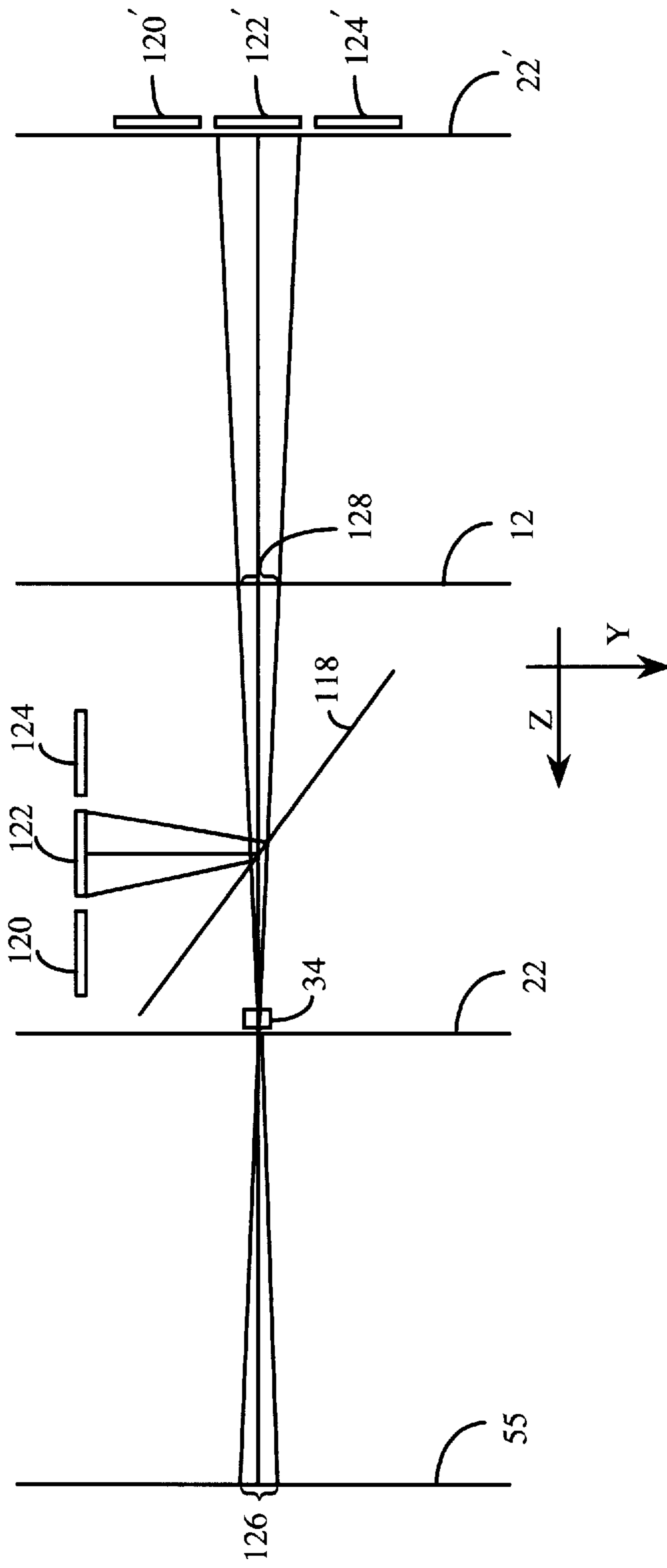


FIG. 9

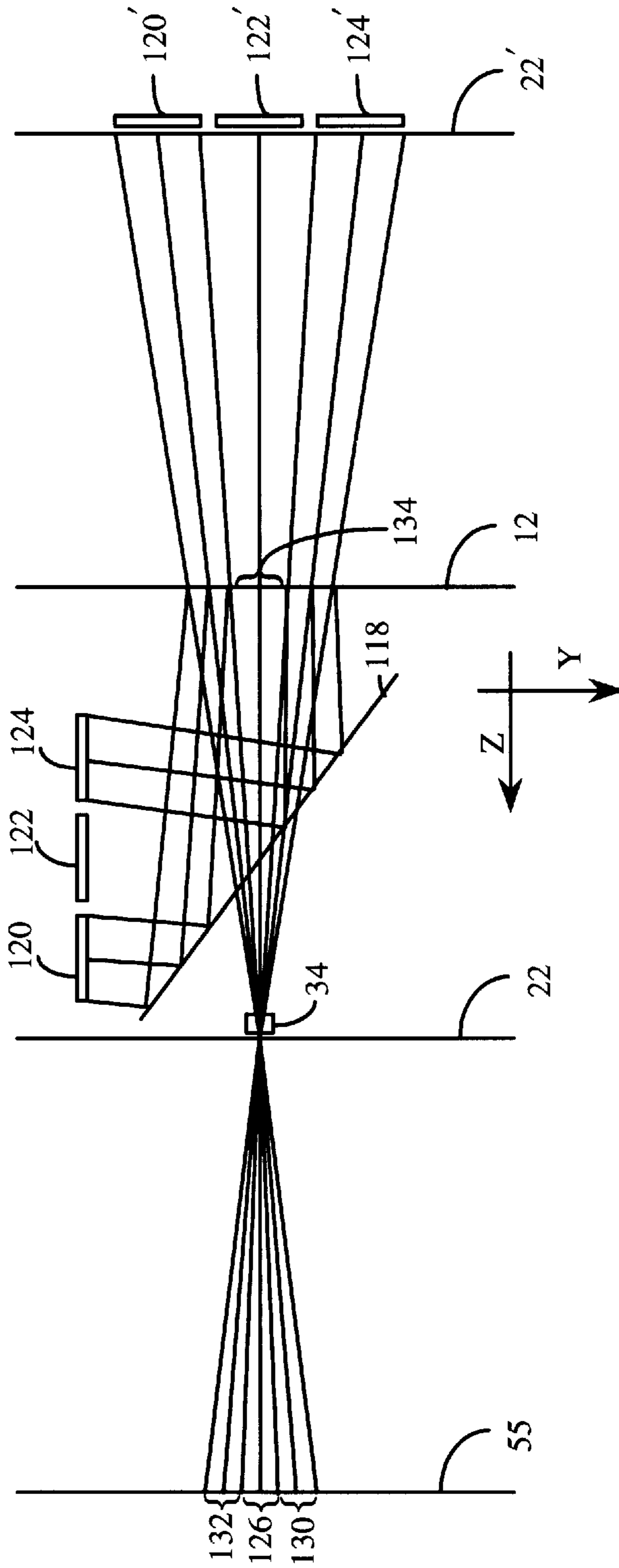


FIG. 10

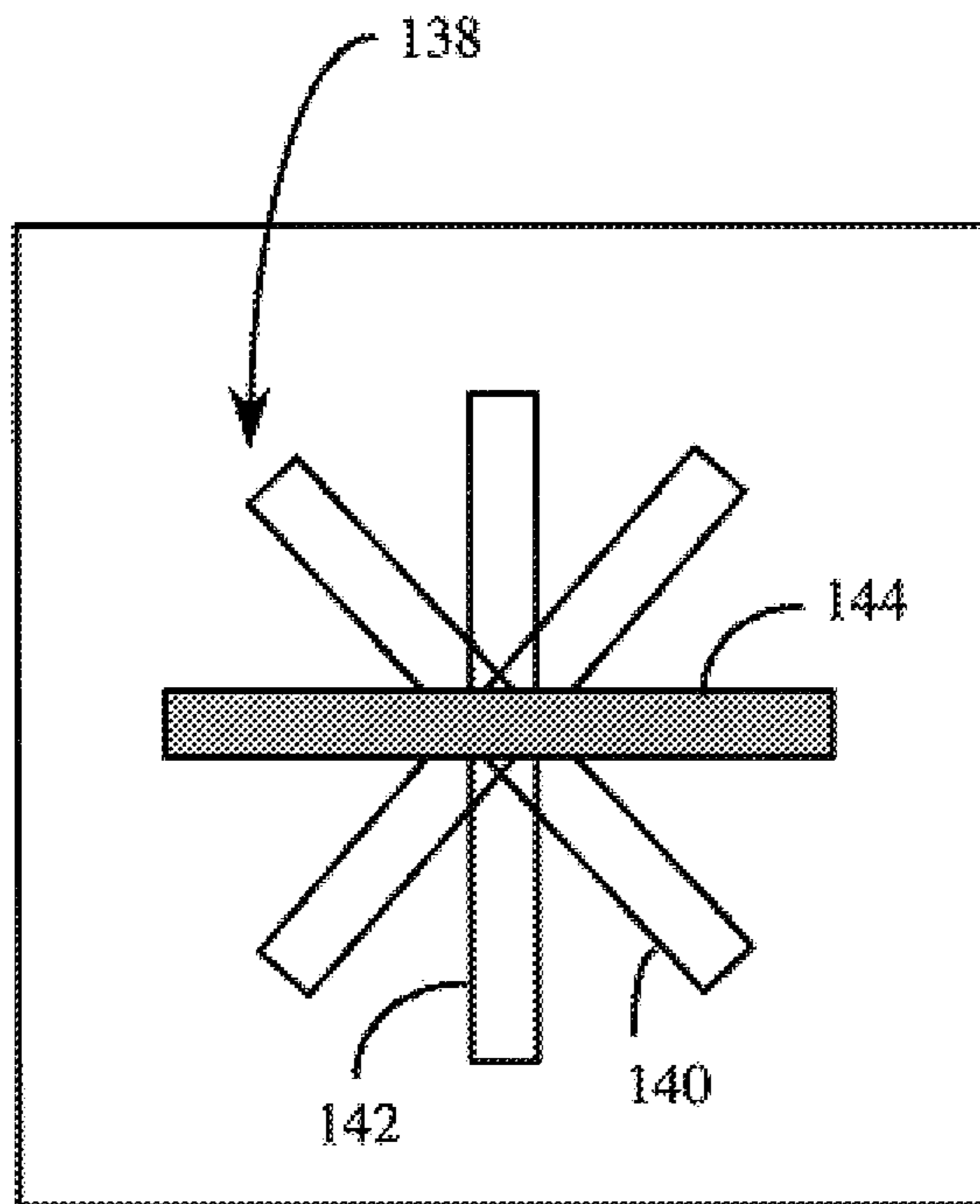


FIG. 11B

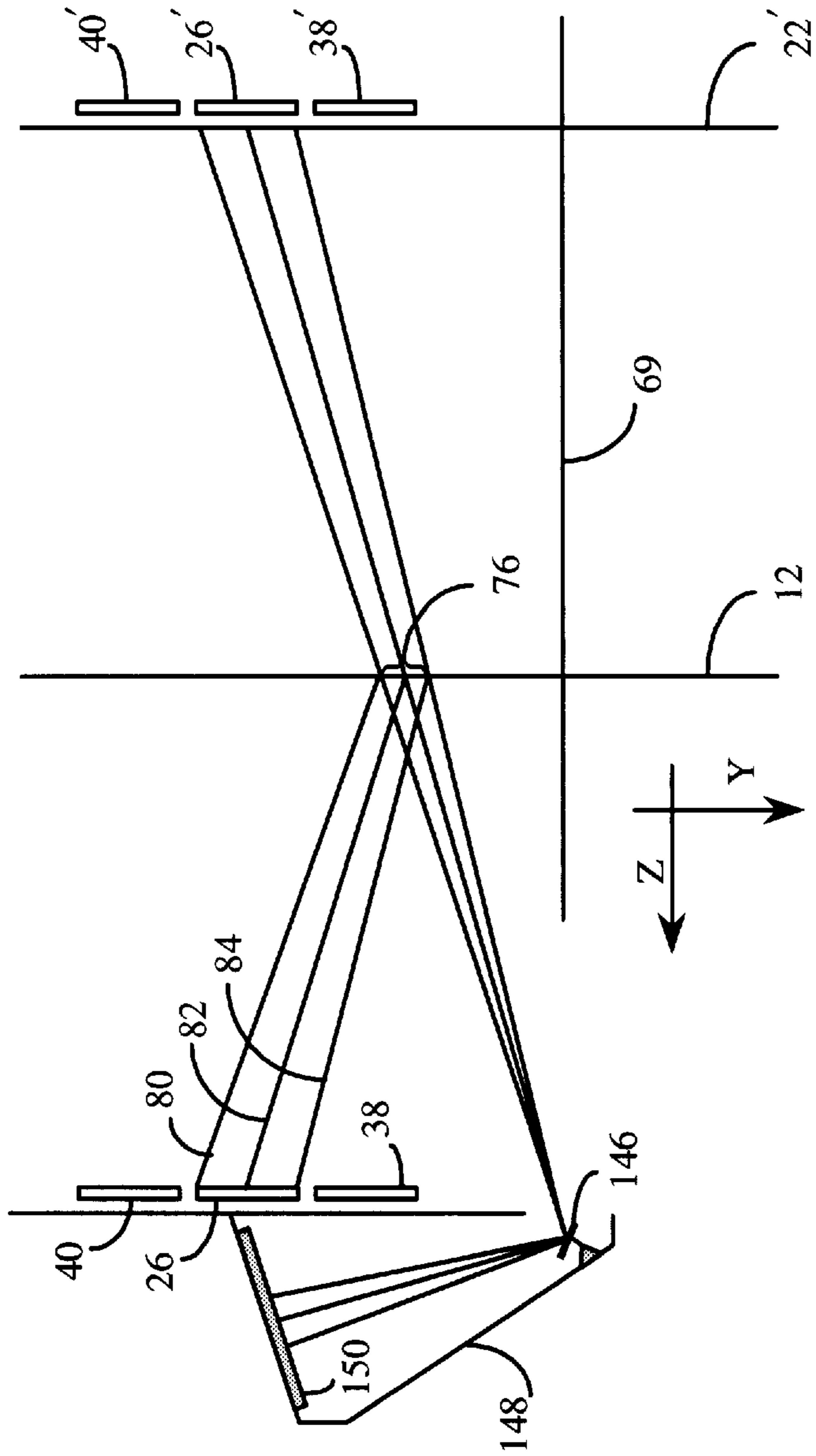


FIG. 12

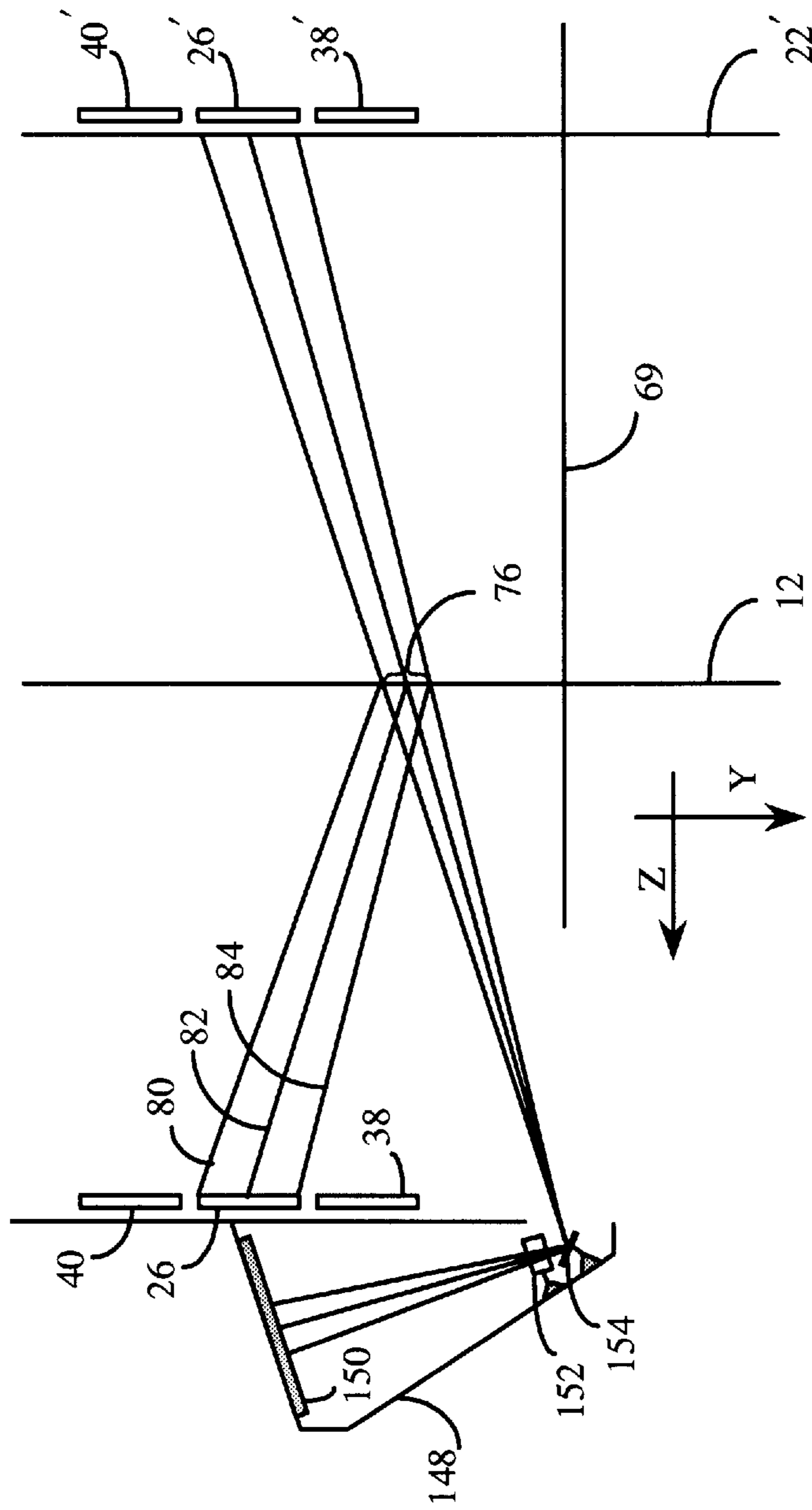


FIG. 13

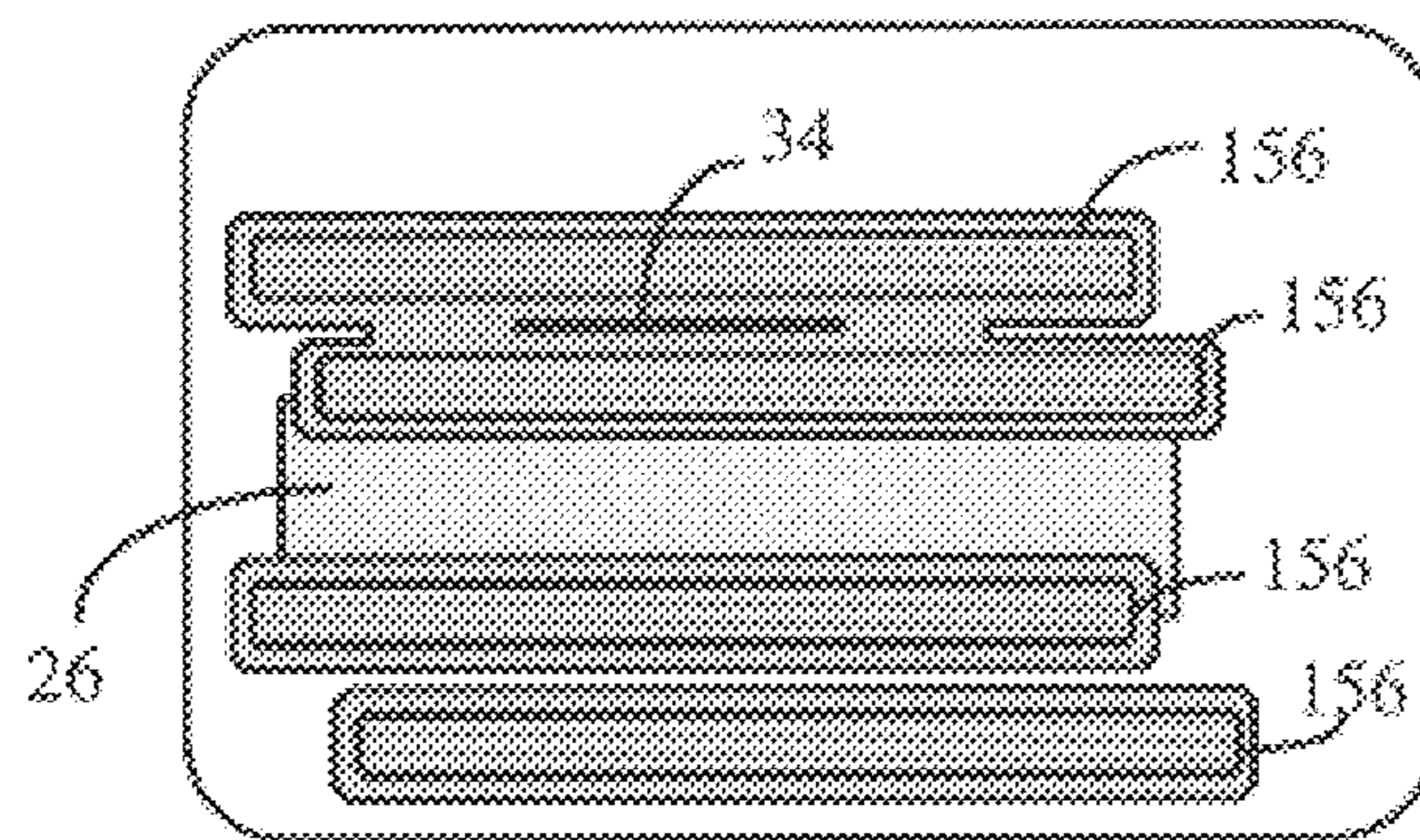


FIG. 14

IMAGE FORMATION APPARATUS FOR VIEWING INDICIA ON A PLANAR SPECULAR SUBSTRATE

This is a continuation of application Ser. No. 08/630,421 filed on Apr. 2, 1996, now abandoned.

FIELD OF THE INVENTION

This invention relates generally to machine vision, and particularly to automated optical detection of indicia, such as alphanumeric characters and fiducial marks, on a mirror-like substrate, such as a semiconductor wafer.

BACKGROUND OF THE INVENTION

Silicon wafers are commonly marked with serial numbers, bar codes, or other indicia for identifying and tracking wafers throughout the process steps of semiconductor device fabrication. Typically, the indicia are created by forming small surface disruptions in an otherwise uniformly flat and reflective (mirror-like or specular) surface of the wafer. These surface disruptions can be formed using a high intensity laser light, or a diamond scribe, for example, to selectively remove or redistribute the material that forms the reflective surface of the wafer, thereby producing small pits in the surface having, for example, a cup-shaped cross-section.

To access the identification and tracking information represented by the indicia, a machine vision system can be used to acquire and analyze an image of the indicia. Image acquisition includes the step of image formation, i.e., forming an image of the indicia on, for example, an image sensor, such as a CCD array in a CCD camera. The CCD array then provides a signal representing the indicia that is digitally processed to determine the information represented by the indicia.

In practice, the step of forming an image of the indicia can be complicated by the presence of irregularities on the wafer surface, or by changes in surface characteristics resulting from the various deposition steps involved in the semiconductor manufacturing process. In fact, known image formation schemes do not provide adequate performance in certain important situations wherein the indicia have been degraded by process steps, resulting in indicia reading errors. Moreover, existing imaging systems are experiencing further difficulties detecting the newer "soft marks". To form a readable image of indicia on the surface of a semiconductor wafer throughout a series of semiconductor process steps, the readability of the output image produced by the image formation system must be unaffected by the consequent changes in the appearance of the indicia.

Known systems for detecting indicia formed in the surface of a semiconductor wafer include a light source for illuminating the surface of the wafer, and a camera that has a lens system with an adjustable circular aperture stop for forming images on an imaging device, such as a CCD array. In such systems, some fraction of the light rays transmitted towards the portion of the wafer surface bearing the indicia are reflected by the wafer surface, and are then received by the camera to form an image of the indicia.

To adapt to the changes in the appearance of the indicia due to the sequence of processing steps, it is known to condition, modulate, shape or otherwise control the transmitted light, i.e., the light rays transmitted towards the portion of the wafer surface bearing the indicia.

For example, it is known to selectively block a portion of the transmitted light, i.e., the set of all light rays emitted by

the light source, before the transmitted light impinges upon the wafer surface. In particular, Wilt et al., U. S. Pat. Nos. 5,231,536, and 5,469,294 teach an illumination system for recognition of indicia on a reflective substrate having a plurality of light sources, and a plurality of opaque masks and/or baffles that stop selected light rays emitted by the light sources from reaching the reflective substrate.

Other methods of controlling transmitted light before it reaches the surface of a mirror-like substrate include collimating the light, such that only light rays characterized by substantially similar angle of incidence impinge upon the surface of the substrate. Light can be substantially collimated by placing the light source at a great distance from the surface of the substrate, or by use of light collimating optics. Also, controlling the angle of incidence of the transmitted light in other ways can be employed.

However, these and other known systems for imaging indicia on a mirror-like substrate tend to be large, expensive to manufacture, and difficult to integrate into existing equipment, such as wafer probers, and other semiconductor device manufacturing equipment. They also tend to be too heavy to mount on existing robot arm assemblies.

SUMMARY OF THE INVENTION

The image formation system of the invention provides a compact apparatus for viewing indicia on a planar mirror-like (specular) substrate, such as a semiconductor wafer. The invention is particularly effective in viewing indicia that require either brightfield illumination or high-angle dark-field illumination.

These and other benefits of the invention are provided in part by providing selective directional focusing and defocusing of the reflected image of the illumination elements that illuminate the indicia, while providing substantial focusing of the image of the indicia at high contrast. The reflected image of the illumination elements are defocused in a selected direction, while remaining focused in a direction that is perpendicular to the selected direction. In the case of high-angle darkfield illumination, such directionally selective focusing maximizes useful darkfield area by minimizing interference between the reflected image of the illumination sources and the image of the indicia, while also maximizing the contrast of the image of the indicia, thereby avoiding a prior art tradeoff between useful darkfield area and indicia image contrast.

Directionally selective focusing is achieved by selecting a plurality of ray bundles from the surface of the substrate, the ray bundles each having an elongated cross section, using an elongated slot aperture, or elongated mirror, for example. At the selector, each ray bundle has the same cross section, which cross section is the cross section of the selector. In the case of an elongated aperture, the cross section is the size and shape of the elongated aperture.

The image formation system of the invention forms a well-focused image of indicia on the surface of a mirror-like planar substrate, while also forming a directionally focused image of one or more illumination elements that illuminate the indicia. The illumination elements can be localized, such as a plurality of light emitting diodes, or can be longitudinally extended, such as a longitudinally extended fluorescent tube. The directionally focused image is defocused along a longitudinal direction and well-focused along a transverse direction. The longitudinal direction is defined by the longitudinal axis of an elongated selector/converger, e.g., an aperture/lens that selects a portion of the reflected light rays, the portion having an elongated cross-section, and con-

verges the selected portion of the reflected light rays upon an image sensor to form an image of the indicia on the image sensor. The image sensor can be electronic, such as a CCD array, can be chemical, such as photographic film, or can be biological, such as a human eye.

In a preferred embodiment of the invention, the selector/converger includes an elongated slot aperture that is cooperative with a lens system that can also include a standard circular aperture of adjustable diameter.

In a preferred embodiment, the elongated slot aperture is formed as a slot in a printed circuit board that also supports a plurality of illumination elements. This printed circuit board is disposed in front of the lens of a video camera such that the only light rays that can enter the lens of the video camera are light rays that traverse the elongated slot aperture.

The printed circuit board includes two sets of lights: a first set adapted to provide darkfield illumination of the indicia, and a second set adapted to provide brightfield illumination. In a preferred embodiment, the second set includes a diffuser disposed in front of a plurality of light emitting elements such that light rays are emitted over a distributed region rather than from a plurality of localized points. In a further preferred embodiment, the first set of illumination elements includes two linear arrays of light emitting elements positioned on either side of the second set.

In darkfield mode, light emitted from the first set is reflected from the mirror-like surface of the wafer that includes the indicia, and is then selected using a slot aperture so as to allow only a selected set of the light rays that have been reflected in a diffuse or non-planar specular manner by the indicia to be received by the video camera. Substantially all of the rays that have been reflected in a planar specular manner do not reach the image detector of the video camera. Thus, in darkfield mode, the indicia appear bright against a dark background.

In bright field mode, diffuse or non-planar reflection from the indicia, or absorption by the indicia, result in light rays that do not reach the camera. Substantially all of the rays that have been specularly reflected reach the image detector of the video camera. Therefore, laser scribed marks appear dark on a bright background.

It is known that the diameter of a circular lens aperture is inversely related to the depth of field of an optical system that includes the circular lens aperture. The apparatus of the invention includes an elongated non-circular aperture that provides a directionally asymmetric depth of field. The invention uses the elongated aperture to provide a light ray acceptance angle that is greater along a direction parallel to the longitudinal axis of a string of indicia than the light ray acceptance angle along a direction that is perpendicular to the longitudinal axis of the string of indicia.

At the image sensor, the illumination elements appear as a virtual image created by reflection of the illumination elements off the wafer surface. This virtual image is located at a position that is twice the actual distance of the illumination elements from the wafer surface. The optical effect of the slot aperture is to "blur" the image of the individual light elements along a direction parallel to the longitudinal axis of the string of indicia, while maintaining relatively sharp focus along a direction transverse to the longitudinal axis. Directionally selective focusing of received light avoids the need to tightly control transmitted light for the purpose of imaging shallow scribes or so called "soft marks". This beneficially results in a substantial size, weight, and cost savings over known implementations of image formation systems for wafer identification.

An unexpected benefit of the use of an elongated slot aperture is an improvement in brightfield illumination. Specifically, due to the longitudinal defocusing of the image of the illumination element diffuser, the image of that diffuser is made more uniform in brightness. This results in more uniform contrast along all portions of the indicia, resulting in an enhanced image signal-to-noise ratio.

Also unexpectedly, further improvements in image signal-to-noise ratio are obtained by improved rejection of ambient light by the slot aperture as compared with a circular aperture having a diameter substantially equal to the length of the slot.

As recognized by the invention, controlling received light provides a less costly and more compact system for controlling the angle of the light rays that are integrated to form a useful output image than controlling transmitted light.

The invention allows simultaneous viewing of features on the planar reflective surface of the substrate, while limiting interference by virtual images of the illumination elements.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be more fully understood from the following detailed description, in conjunction with the accompanying figures, wherein:

FIG. 1A is a perspective view of a preferred embodiment of the invention in a direct viewing position with respect to a planar reflective substrate;

FIG. 1B is a view of the embodiment of FIG. 1A as seen from the planar reflective surface showing a plurality of lighting elements, a diffuser region, and an elongated slot aperture;

FIG. 1C is a side view of a preferred embodiment of the invention in an indirect viewing position with respect to a planar reflective substrate, and a cooperative mirror assembly;

FIG. 2 is an exploded perspective view of the components of the embodiment of FIG. 1A;

FIG. 3A is a view as seen from the planar reflective substrate of another preferred embodiment of the invention having a non-circular lens integrated with a printed circuit board, also showing a plurality of LEDs, an elongated slot aperture, and a diffuser region;

FIG. 3B is a view, as seen from the planar reflective surface, of the non-circular lens of FIG. 3A, also showing a phantom outline of a circular lens from which the non-circular lens of FIG. 3A can be derived;

FIG. 3C is a side view of the embodiment of FIG. 3A, showing the LED, an image sensor, and an associated light shroud;

FIG. 4 is a ray diagram of a darkfield mode where only rays that traverse the elongated aperture of the invention, after being reflected from a planar reflective portion of the substrate are shown;

FIG. 5 is a ray diagram of a brightfield mode where only rays that traverse the elongated aperture of the invention, after being reflected from a planar reflective portion of the substrate are shown;

FIG. 6 is a marginal ray diagram showing marginal rays originating from real features of the reflective planar substrate, and virtual features of a virtual image of the illumination elements;

FIG. 7 is a ray diagram of a first mode of an extended darkfield embodiment of the invention;

FIG. 8 is a ray diagram of a second mode of an extended darkfield embodiment of the invention;

FIG. 9 is a ray diagram of a brightfield mode of an coaxial embodiment of the invention;

FIG. 10 is a ray diagram of a darkfield mode of an coaxial embodiment of the invention;

FIGS. 11A and 11B illustrate an embodiment of the invention having a plurality of possible elongated slot apertures;

FIG. 12 is a ray diagram of a brightfield mode where only rays that are reflected by a slice of a focusing mirror of the invention, after being reflected from a planar reflective portion of the substrate are shown;

FIG. 13 is a ray diagram of a brightfield mode where only rays that are reflected by a slice of a planar mirror and focused by a slice of a lens, after being reflected from a planar reflective portion of the substrate are shown; and

FIG. 14 is a view as seen from the planar reflective surface of a plurality of elongated lighting elements, a diffuser region, and an elongated slot aperture.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIGS. 1A and 1C, an embodiment of the image formation apparatus of the invention 10 is shown in various operating positions with respect to a mirror-like substrate 12, such as a semiconductor wafer or magnetic recording media, the substrate 12 having indicia 14 on its reflective surface. In FIG. 1A, the image formation apparatus 10 is in a direct illumination and viewing position.

FIG. 1C shows the image formation apparatus 10 in an indirect viewing and illuminating position, wherein the optical paths for viewing and illumination are folded by a mirror assembly 16. Those skilled in the art will appreciate that many other indirect viewing and illuminating positions are made possible by other mirror arrangements. The indirect viewing and illuminating positions, such as shown in FIG. 1C, are important for use in conjunction with some of the current installed base of semiconductor device fabrication equipment that provide only limited space for illuminating and viewing apparatus.

As can be seen in FIGS. 1A and 2, the image formation apparatus of the invention includes, in a preferred embodiment, a standard video camera 18, and a lens 20 such as a Pulnix TM-7EX camera with a D.O. Industries Navitron TV lens, being 25 mm and F 1.4. This preferred embodiment also includes a printed circuit board 22, having a plurality of illumination elements 24 and 25, such as a plurality of round and rectangular light emitting diodes (LEDs).

Further, this embodiment includes a diffuser layer 26 for brightfield illumination having cut-out areas and diffuser areas. In masking relationship with the diffuser layer 26 is the opaque mask layer 28 that has cut-out areas that expose both the diffuser layer 26 and the illumination elements 24 directly. Rectangular LEDs 25 reside behind the unmasked portion of the diffuser layer 26.

Referring to FIG. 1B, the apparatus 10 of FIG. 1A is seen from the position of the reflective substrate 12, e.g., a semiconductor wafer. As discussed above, there is a plurality of illumination elements 24, e.g., an array of LEDs 24. Also, there is a diffuser region 26 for providing brightfield illumination, behind which is a plurality of rectangular LEDs 25 (not shown in this view).

Also, a slot aperture 34 is disposed between rows of LEDs. 24. The slot aperture 34 is formed, in this preferred embodiment, as a cut-out portion of the printed circuit board (PCB) 22. The slot aperture 34 provides the only paths from

the surface of the reflective substrate to the lens 20 and ultimately to the image sensor (not shown) of the camera 18. Preferably, the slot aperture has a generally rectangular shape, having a longitudinal dimension and a transverse dimension, where the transverse dimension is determined empirically so as to obtain a useful darkfield region with the widest possible slot aperture, so as to provide the brightest image of the indicia, without interference (overlap) by the illumination sources. The longitudinal dimension can be anywhere within a range from extent of the free aperture of the lens system to about the extent of the transverse dimension.

The elongated aperture need not be rectangular; it can also be ellipsoidal, trapezoidal, race-track-like (having circular ends and straight longitudinal sides), or any other longitudinally extended shape.

In the preferred embodiment of FIG. 1B, the slot aperture is rectangular and has a length of 0.5 inches, and a width of about 0.035 inches.

The LEDs 24 are arranged in rows, each row being a different distance from the center line 25 of the brightfield illumination element 26, so as to provide either high angle darkfield illumination, or low angle darkfield illumination. In particular, rows 38 and 40 are for providing high angle darkfield illumination, and are about 0.3 inches from the center line 25 of the brightfield illumination element 26, for example. Thus, the closer a row of LEDs is to the center line 25 of the brightfield illumination element 26, the higher the angle of the darkfield illumination.

Also, rows 36 and 42 are for providing lower angle darkfield illumination. For example, rows 36 and 42 are each about 0.6 inches from the slot aperture 34.

In an alternate embodiment, only rows 38 and 40 are used to provide high angle darkfield illumination, and rows 42 and 36 are not included. Thus, an embodiment characterized by a transverse dimension smaller than the transverse dimension of the embodiment shown in FIG. 1A can be provided. A smaller transverse dimension can be useful in some applications where only limited space is available, such as some existing semiconductor manufacturing machinery, e.g., a wafer prober.

Referring again to FIGS. 1A and 2, an opaque baffle 30 surrounds most of the lens 20 and illumination elements 24. The opaque baffle 30 serves both to substantially inhibit light emitted by the illumination elements 24 from illuminating the substrate 12 via paths other than through the cut-out areas of the opaque mask layer 28, and to substantially inhibit ambient light from entering the lens 20 via any path that does not pass through the cut-out areas of the opaque mask layer 28.

The printed circuit board 22, and the illumination elements 24 and 25 thereon, are energized via a connector 32.

The working distance, i.e., the distance from the opaque mask layer 28 of this embodiment 10 of the image formation apparatus of the invention to the substrate 12, depends both on the type of lens used, and the desired field of view. For example, a 16 mm or 25 mm lens can be used at a working distance of about 3 to 4 inches. It is preferable to use a zoom lens that allows a constant working distance, while providing a variable image size of the indicia 14.

Referring again to FIG. 2, an exploded assembly diagram is shown that illustrates how the layers 26 and 28, the PCB 22, the lens 20 and the camera 18 are assembled. Specifically, screws 46, brackets 48, and posts 50 are used to space the various components such that the components are as close as possible, without touching. The distance of

the slot aperture **34** in the PCB **22** from the lens **20** is not critical. In fact, the slot can advantageously be included within the lens system, before the lens system, or after the lens system. Specifically, a slot aperture can be included between the image sensor of the camera **18** and preferably close to the lens **20**. Alternatively, an elongated slot aperture can be painted on the lens **20** using opaque paint, or other opaque coating.

In another preferred embodiment, shown in FIGS. **3A**, **3B**, and **3C**, a lens **52** is integrated with a printed circuit board (PCB) **54** to provide a highly compact embodiment of the invention. Since, according to the invention, only rays of light that pass through a slot aperture are permitted to reach an image sensor **55**, only a portion of a lens **56** is included by removing non-functional portions of the lens **56**, thereby providing the lens **52**. Only the operative portions of the lens **56** are retained, thereby allowing a row of LEDs **58** to reside close to the slot aperture **60** so as to provide high angle darkfield illumination. The image sensor **55** is enclosed within an opaque cavity formed by an enclosure **62** so as to ensure that only light passing through the slot aperture **60** reaches the image sensor **55**.

Referring again to FIG. **1A**, the scribed indicia **14** on the reflective planar substrate **12** can be formed by laser ablation, for example, and can have various depths and cross-sections. Some indicia consist of a pattern of shallow pits, called "soft marks", each pit having a cross-section that results in non-planar specular reflection, and/or diffuse reflection, and/or absorption. Consequently, under brightfield illumination, such pits should appear darker than their surroundings, and under darkfield illumination, such pits should appear brighter than their surroundings. However, such pits (soft marks) are difficult to view because they tend to cause only minor deviations from planar specular surface behavior. In practice, it is found that softmarks are best viewed under "high angle" darkfield illumination, where "high angle" means at an angle close to 90 degrees from the plane of the substrate being viewed, i.e., between about 85 degrees and 90 degrees. In this way, the brightness of the image of the softmark indicia is maximized.

However, prior to the invention, high angle darkfield illumination was difficult to achieve in the case of an image formation apparatus for viewing highly reflective planar surfaces. This was due to the fact that the image of the illumination elements of the lighting system tends to interfere with the image of the soft mark indicia. This occurs because, at high angle darkfield illumination, the virtual image of the lights is very close to the image of the indicia. Also, since the softmark indicia do not appear bright compared with the light source, the round aperture stop of the camera must be opened as wide as possible to allow maximum illumination of the softmark indicia. However, when the round aperture is widely open, the depth of field of the lens system of the camera is reduced. Consequently, the image of the illumination elements can become defocused and extend over the image of the softmark indicia, thereby rendering them effectively undetectable.

As recognized by the invention, the solution to this multiple dilemma is elegantly provided by use of the elongated slot aperture **34** cooperative with the lens system **20** of the camera. To adjust the effective longitudinal extent of the elongated slot aperture, an adjustable round aperture, such as an iris diaphragm (not shown) can also be included. In the absence of an adjustable round aperture, the effective length of the elongated slot aperture **34** is determined by the diameter of the clear aperture of the lens system **20**.

Referring to FIGS. **1B** and **4**, to achieve high angle darkfield illumination, a set of illumination elements **38**

and/or **36** is disposed close (e.g., 0.3 inches) to the center line **25** of the brightfield illumination element **26**.

In the case of the set of illumination elements **38** as shown in FIG. **4**, each illumination element radiates multi-directionally. Light emitted from an illumination element can be usefully represented by a plurality of light rays, each light ray originating from the illumination element and extending in a particular direction. Thus, in the case of a point-source illumination element that radiates multi-directionally, a plurality of light rays emanate from the point-source, each light ray being characterized by a unique angle. Further, in the case of an illumination element having a surface area, such as a light emitting diode (LED), for each point on the surface, a plurality of light rays emanate, each light ray being characterized by a unique angle.

In the present invention, only a portion of the light rays emitted by each LED are reflected and ultimately traverse the elongated slot aperture **34** to reach the image sensor, thereby contributing to formation of an image at the image plane **55**. In the case of planar specular reflection of the light rays emitted by the illumination element **38** that also traverse the elongated aperture **34**, that portion is represented by three example light rays **62**, **64**, **66**. Thus, a real image **68** of the illumination element **38** forms at the image plane **55**. Likewise, a real image **70** of the illumination element **40** also forms at the image plane **55**. Also note that due to the planar specular reflection at the surface of the substrate **12**, there is a virtual image **38'** of the illumination element **38** at the virtual image plane **22'**.

In particular, of all of the light rays that are emitted by the illumination element **38**, and that traverse the elongated slit **34** by way of a specular planar reflection at the substrate **12**, the ray **62** represents the light ray having the lowest angle of incidence with respect to the planar substrate **12** (or with respect to an axis **69** that is perpendicular to the planar substrate **12** that also intersects a midpoint of the elongated aperture **34**).

Analogously, the ray **66** represents the light ray having the highest angle of incidence, and the ray **64** represents the light ray having an intermediate angle of incidence, each such light ray also traversing the elongated slit **34** by way of a specular planar reflection at the substrate **12**.

Similarly, the rays **62A**, **64A**, and **66A** emitted by the illumination element **40** provide an alternate and/or additional source of high angle darkfield illumination than the ray bundle represented by the rays **62**, **64**, **66**. Also, the rays **62A**, **64A**, and **66A** contribute to forming a real image **70** of the illumination element **40** at the image plane **55**.

In the darkfield mode of operation represented by FIG. **4**, only illumination elements **38** and **40** are energized. As explained above, a real image **68** of the illumination element **38** forms at the image plane **55**, and a real image **70** of the illumination element **40** forms at the image plane **55**. If the surface of the substrate **12** is specular (mirror-like) and planar, then a substantially dark darkfield region **72** is formed at the image plane **55**, the darkfield region **72** being bounded by the real images **68** and **70** of the illumination elements **38** and **40**. The darkfield region **72** is substantially dark because there is no light ray that is emitted from a dark field illumination element (**38** or **40**) that traverses the elongated slit by way of a specular planar reflection at the substrate plane **12**, thereby reaching the darkfield region **72** of the image plane **55**.

For purposes of diagrammatic clarity, FIG. **4** shows only those rays that traverse the elongated aperture **34**, after being reflected in a specular planar manner. For example, rays that

are reflected in a specular planar manner, but do not traverse the elongated aperture **34**, do exist, but are not explicitly shown in FIG. **4**, or in any of the other figures in this patent document. This is because such rays do not contribute to image formation at the image plane **55**. There is a class of rays that are emitted by one of the darkfield illumination elements **38** or **40**, however, that do contribute to image formation at the image plane **55**, and do so within the region **72** of the image plane **55**. Such rays impinge upon the region **74** of the substrate **12** having the indicia. Due to optical properties of the indicia that differ from the optical properties of the unmodified mirror-like substrate **12**, some rays are reflected by the indicia so as to traverse the elongated aperture **34** and then form an image of the indicia **14** at the image plane **55** within the region **72**. This image will be focused in both the longitudinal and transverse directions of the elongated aperture **34**, because the indicia **14** reside on the substrate **12**, which is disposed within both the longitudinal and transverse depths of field.

The optical properties of the indicia that differ from the optical properties of the unmodified mirror-like substrate **12** are optical properties that result in non-planar and/or non-specular reflection at the surface of the substrate **12** in the indicia window **74**. By non-planar reflection, we mean reflection due to a region that is either not flat, e.g., curved, or is flat, but the flat region is not oriented in the same direction as the orientation of the major plane of the substrate **12**.

Thus, light rays emitted by the darkfield illumination elements **38** and **40** are reflected by the indicia **14** in a way that is either not specular, e.g. diffusely reflected, or is specular but is not planar, so as to allow light rays emitted by the darkfield illumination elements **38** and **40** to impinge upon the darkfield region **72**. Consequently, in the darkfield illumination mode, an indicia **14** located within an indicia window **74** will appear bright against the darkfield region **72** in an image formed at the image plane **55**. For a discussion of specular and diffuse reflection, see page 67 of *Optics* by Eugene Hecht and Alfred Zajac, copyright 1974 by Addison-Wesley Publishing Co., Inc, the entire book being hereby incorporated by reference.

An example of specular, non-planar reflection is provided by the case of "soft marks" composed of a plurality of small pits, each pit having at least one non-planar specular region. In particular, if each pit is formed by creating a conical void in the surface of the substrate **12**, such that the pit has a curved and specular inner surface, such pits would appear bright against a dark background. Alternatively, if each pit is formed by creating a tetrahedral void in the surface of the substrate, wherein one of the triangular planes of the tetrahedron is co-planar with respect to the major plane of the substrate **12**, then the pit so-formed will have three flat triangular inner surfaces. Each of the three flat triangular inner surfaces will not be co-planar with respect to the major plane of the substrate **12**, nor will any of the three flat triangular inner surfaces be oriented in the same direction as the direction of the major plane of the substrate **12**. Consequently, an image of such a pit will appear bright against a dark background.

FIG. **5** illustrates a brightfield mode of operation of the invention. In the preferred embodiment of FIG. **5**, to achieve brightfield illumination, a brightfield illumination element **26** is disposed between the two darkfield illumination elements **38** and **40**.

In FIG. **5**, each point on the illumination element **26** radiates multi-directionally. In the case of an illumination

element having a surface area, such as a diffuser disposed in front of a plurality of light emitting diodes (LEDs), for each point on the surface, a plurality of light rays emanate, each light ray being characterized by a unique angle.

In the present invention, only a portion of the light rays emitted by the illumination element **26** are reflected by the substrate **12** and ultimately traverse the elongated slot aperture **34** to reach the image sensor, thereby contributing to formation of an image at the image plane **55**. In the case of planar specular reflection of the light rays emitted by the illumination element **26** that also traverse the elongated aperture **34**, that portion is represented by three example light rays **80**, **82**, and **84**. Thus, a real image **78** of the illumination element **26** forms at the image plane **55**. Also note that due to the planar specular reflection at the surface of the substrate **12**, there is a virtual image **26'** of the illumination element **26** at the virtual image plane **22'**.

In particular, of all of the light rays that are emitted by the illumination element **26**, and that traverse the elongated slit **34** by way of a specular planar reflection at the substrate **12**, the ray **80** represents the light ray having the lowest angle of incidence with respect to the planar substrate **12** (or with respect to an axis **69** that is perpendicular to the planar substrate **12** that also intersects a midpoint of the elongated aperture **34**).

Analogously, the ray **84** represents the light ray having the highest angle of incidence, and the ray **82** represents the light ray having an intermediate angle of incidence, each such light ray also traversing the elongated slit **34** by way of a specular planar reflection at the substrate **12**.

In the brightfield mode of operation represented by FIG. **5**, only the illumination element **26** is energized. A real image **78** of the illumination element **26** forms at the image plane **55**. This real image **78** is out of focus along the longitudinal direction of the elongated aperture **34**, i.e., in the X-direction of FIG. **5**, and is in focus in the transverse direction of the elongated aperture **34**, i.e., in the Y-direction of FIG. **5**. If the surface of the substrate **12** is uniformly specular (mirror-like) and planar, and the brightfield illumination element **26** emits light substantially uniformly over its area, then a substantially uniformly bright brightfield region **78** is formed at the image plane **55**. In fact, the elongated slot aperture enhances the uniformity of the brightfield region **78** due to the directional defocusing caused thereby. The brightfield region **78** is substantially uniformly bright because substantially all light rays that are emitted from the bright field illumination element **26**, and that traverse the elongated slit, are reflected in a specular and planar manner at the substrate plane **12**, and consequently reach the brightfield region **78** to form an image of the brightfield illumination element **26** at the image plane **55**.

For purposes of diagrammatic clarity, FIG. **5** shows only those rays that traverse the elongated aperture **34**, after being reflected in a specular planar manner by the substrate **12**. For example, rays that are reflected in a specular planar manner, but do not traverse the elongated aperture **34**, do exist, but are not explicitly shown in FIG. **5**, or in any of the other figures in this patent document. This is because such rays do not contribute to image formation at the image plane **55**.

There is a class of rays that are emitted by the brightfield illumination element **26**, however, that do contribute to image formation at the image plane **55**, and do so within the region **78** of the image plane **55**. Such rays impinge upon the region **76** of the substrate **12** having the indicia **14**. Due to optical properties of the indicia **14** that differ from the optical properties of the unmodified mirror-like substrate **12**,

some rays are reflected by the indicia **14** so as to not traverse the elongated aperture **34** and therefore not reach the image plane **55** along with the rest of the rays that form the image of the illumination source **26** within the region **78**. In effect, a negative image of the indicia **14** is formed, where an absence or diminution of light intensity at a point on the image plane **55** indicates the presence of a portion of the indicia **14**. This negative image of the indicia **14** will be focused in both the longitudinal and transverse directions of the elongated aperture **34**, because the indicia **14** reside on the substrate **12**, which is disposed within both the longitudinal and transverse depths of field.

The optical properties of the indicia **14** that differ from the optical properties of the unmodified mirror-like substrate **12** are optical properties that result in non-planar and/or non-specular reflection of light, or absorption of light at the surface of the substrate **12** in the region **76** that includes the indicia **14**. By non-planar reflection, we mean reflection due to a region that is either not flat, e.g., curved, or is flat, but the flat region is not oriented in the same direction as the orientation of the major plane of the substrate **12**.

Thus, light rays emitted by the brightfield illumination element **26** are reflected by the indicia **14** in a way that is either not specular, e.g. diffusely reflected, or is specular but is not planar, or is absorbed, so as to prevent light rays emitted by the brightfield illumination element **26** from impinging upon the brightfield region **78** of the image plane **55**. Consequently, in the brightfield illumination mode, an indicia **14** located within an indicia window **76** will appear dark against the brightfield region **78** in an image formed at the image plane **55**. For a discussion of specular and diffuse reflection, see page 67 of *Optics* by Eugene Hecht and Alfred Zajac, copyright 1974 by Addison-Wesley Publishing Co., Inc, the entire book being hereby incorporated by reference.

An example of light absorption is provided by the case of a plurality of dots on the substrate **12**, each dot being formed by a quantity of substantially non-reflective black paint, pigment, or the like. Such dots would appear dark against a bright background.

While FIGS. **4** and **5** show the behavior of selected light rays as shown looking along the longitudinal direction as defined by the elongated aperture **34**, i.e., looking along the X-axis of FIGS. **4** and **5**, FIG. **6** illustrates the behavior of other selected light rays as seen looking along a transverse direction with respect to the elongated aperture **34**, i.e., looking along the Y-axis of FIGS. **4** and **5**.

In particular, the solid sloping lines **86** represent focused marginal rays, so-called because the marginal rays **86** travel from a real object point (e.g., a portion of the indicia **14**) on the axis **69** to the rim or margin of the clear aperture of the lens **88**, which then converge towards the image plane **55**.

By contrast, the broken sloping lines **90** represent directionally unfocused marginal rays, so-called because the marginal rays **90** travel from a virtual object point (e.g., a point of a virtual image of an illumination element) on the axis **69** to the rim or margin of the clear aperture of the lens **88**, which then converge towards the image plane **55**, but does not focus at the image plane **55** along the longitudinal or X-direction.

Thus, real objects, such as indicia on the substrate **12**, are in focus along the X-direction at the image plane **55**, while virtual objects, such as virtual images of the illumination source **26** at the virtual image plane **22'**, are out of focus along the X-direction.

Simultaneously, real objects, such as indicia on the substrate **12**, are in focus along the Y-direction at the image

plane **55**, while virtual objects, such as virtual image of the illumination source **26** at the virtual image plane **22'**, are in focus along the Y-direction.

Thus, real objects, such as indicia on the substrate **12**, are in focus along both the X- and Y-directions at the image plane **55**, while virtual objects, such as virtual image of the illumination source **26** at the virtual image plane **22'**, are both in focus along the Y-direction, and out of focus along the X-direction. Accordingly, the image of the virtual objects at the virtual image plane, such as the virtual image of the illumination source **26** is termed "directionally focused". Directional focusing in the present invention is due to the optical action of the elongated aperture **34**, or the like.

According to the invention, the optical action of the elongated aperture is to create directionally differential depths of field, i.e., the depth of field for focusing in the X-direction is different from the depth of field for focusing in the Y-direction. The depth of field of an optical system is the range of distances along the Z-direction from the optical system within which objects are substantially in focus. Commonly, the depth of field of an optical system is the same along all directions perpendicular to the optical axis of an optical system.

According to the invention, the substrate is located so as to reside within the depth of field in both the X- and Y-directions of the optical system that includes the lens **88** and the elongated aperture **34**. Consequently, the substrate, and the indicia disposed upon it, are in focus at the image plane **55** in all directions. Also according to the invention, the virtual images of the illumination sources at the imaginary image plane **22'** resides only within the depth of field in the Y-direction, and not within the depth of field in the X-direction. Consequently, the virtual images of the illumination sources are directionally out of focus along the X-direction at the image plane **55**, as shown in FIG. **6**.

FIGS. **7** and **8** show first and second operation modes, respectively, of an extended darkfield embodiment of the invention. In the first operation mode, a first set of illumination elements **91**, **92**, and **96** are energized, and in the second operation mode, a second set of illumination elements, in interleaved relationship with the first set, is energized. An extended darkfield image results from combining a first image **98** having a first plurality of darkfield regions **102**, **104** formed at the image plane **55** in the first operation mode, with a second image **100** having a second plurality of darkfield regions **106**, **108** formed at the image plane **55** in the second mode.

The darkfield regions **102** and **104** at the image plane **55** correspond to the regions **110** and **112**, respectively, of the substrate **12**. Similarly, the darkfield regions **106** and **108** at the image plane **55** correspond to the regions **114** and **116**, respectively, of the substrate **12**.

The combined regions **110**, **114**, **112**, and **116** taken together are four times the width of a single darkfield region. Consequently, relatively large indicia, or indicia that are oriented transversely to a single darkfield region, can be imaged at the image plane **55** in this extended darkfield embodiment.

In a preferred embodiment, the images **98** and **100** are combined using a technique called "digital intensity minimization", wherein a per-pixel comparison of the first darkfield image **98** and the second darkfield image **100** is performed, the darker pixel of each per-pixel comparison being retained to be the corresponding pixel of the resulting extended darkfield image. Since almost every pixel of a darkfield region is darker than almost every pixel of a

brightfield image, the resulting extended darkfield image is effectively the interleaved combination of the darkfield regions of each darkfield image **98** and **100**.

Additional illumination elements have been added to the embodiment of FIG. **4** to provide the extended darkfield embodiment of FIGS. **7** and **8**. Illumination elements can be added to either side of the elongated aperture **34**. FIGS. **7** and **8** show an embodiment having three additional illuminations elements **92**, **94**, **96** symmetrically disposed about the elongated aperture **34**. Further additional illumination elements can be added to provide an even larger extended darkfield region.

Another advantage of an extended darkfield region is that it allows the elongated aperture to be rotated with respect to an indicia so as to enhance the readability of the indicia by the image formation system of the invention. The elongated aperture is rotated together with all of the illumination elements. Rotation of the aperture together with a plurality of illumination elements can be achieved by physically rotating the entire image formation apparatus, or can be achieved without physically rotating the entire image formation apparatus using a multi-aperture embodiment described below in conjunction with FIGS. **11A** and **11B**.

For example, FIG. **11A** shows an independently addressable array of illumination elements **136**, such as small LEDs or active matrix transistors, cooperative with an aperture selector **138** of FIG. **11B** that can provide an elongated aperture of any selected shape, width, length, and angular orientation. The rays **137** are shown for an active portion of the array of illumination elements **136** to illuminate the section **128** of the substrate **12**. For example, FIG. **11B** shows three possible elongated slot apertures **140**, **142**, and **144** of rectangular shape, each with the same width and length, but at three different angular orientations. In principle, other angular orientations, shapes, widths and lengths are possible as well.

It is advantageous that only one possible elongated aperture be open to transmission of light at any one moment. For example, in FIG. **11B**, only aperture **144** can transmit light. The aperture selector **138** can be implemented as an array of independently addressable liquid crystal shutter elements, that each can either block or transmit light.

An aperture selector **138** can also be implemented mechanically as an elongated opening in a rotatable disk.

Actual rotation of the elongated aperture with the illumination elements, or effective rotation of the elongated aperture with the illumination elements using the embodiment of FIGS. **11A** and **11B**, for example, provides a further advantage in that some indicia, or portions of some indicia, can become more detectable. For example, if an indicia consisted of groupings of diagonal v-shaped channels, such indicia may be more detectable if the elongated aperture and the illumination elements were rotated into alignment with the diagonal channels.

FIGS. **9** and **10** illustrate brightfield and darkfield modes of operation, respectively, of an on-axis embodiment of the invention. This embodiment employs a half-mirror **118**, that provides one way to avoid problems associated with the illumination elements obstructing the main optical path through the aperture/lens system of the invention. In the brightfield mode of FIG. **9**, a central illumination element **122** emits substantially unfocused light, which light is then reflected partially at a half-mirror **118**. About half of the light impinges upon the substrate **12**, which is then reflected from each point on the substrate that exhibits planar specular reflection back to the half-mirror **118**. The half-mirror **118**

transmits half of the light so-reflected towards the elongated slot aperture **34**, which allows a portion of the light, based on the cross-sectional area of the aperture, to traverse the lens and ultimately form an image on the image plane **55**.

The image is a brightfield image **126** of the indicia **14** located within the region **128** of the substrate **12**.

In the darkfield mode of FIG. **10**, darkfield illumination elements **120** and **124** emit substantially unfocused light, which light is then reflected partially at a half-mirror **118**. About half of the light impinges upon the substrate **12**, which is then reflected from each point on the substrate that exhibits planar specular reflection back to the half-mirror **118**. The half-mirror **118** transmits half of the light so-reflected towards the elongated slot aperture **34**, which allows a portion of the light, based on the cross-sectional area of the aperture, to traverse the lens and ultimately form an image of the indicia **14** and the darkfield illumination elements **120** and **124** on the image plane **55**. The image is a darkfield image **126** of the indicia **14** located within the region **134** of the substrate **12**. An image of the illumination elements **120** and **124** form in regions **130** and **132**, respectively, on the image plane **55**.

In another embodiment, shown in FIG. **12**, the elongated aperture **34** and the lens (not shown) of FIG. **5** are replaced by a slice of a focusing mirror **146**. An enclosure/support **148** supports both the mirror **146** and an image sensor **150**. The enclosure/support **148** also shields the image sensor **150** from ambient light.

The slice of the focusing mirror **146** is obtained by taking a slice of an off-axis focusing reflector, having a shape determined by parabolic and higher order terms, the values of which are determined by the desired focal length, and the desired optical path folding angle, for example, which are each application-specific, as is understood by those skilled in the art of focusing mirror design.

Referring to FIG. **13**, the slice of the focusing mirror **146** of FIG. **12** is replaced by a slice of a focusing lens **152**, and a slice of a mirror **154**. In this embodiment, the slice of the mirror **154** serves to select a bundle of rays having an elongated cross section, and then those rays are converged upon the image sensor **150** to provide the same functionality as the embodiment of FIG. **5**, for example.

With reference to FIG. **14**, the LED's **24** of FIG. **1B** are replaced by elongated illumination elements **156**, also showing the elongated aperture **34**, and the diffuser **26**. Elongated illumination elements can be implemented as fluorescent tubes, elongated plasma discharge tubes, long incandescent filaments, or lossy wave guides having an illumination source at one or both ends of each elongated element **156**.

Other modifications and implementations will occur to those skilled in the art without departing from the spirit and the scope of the invention as claimed. Accordingly, the above description is not intended to limit the invention except as indicated in the following claims.

What is claimed is:

1. An apparatus for forming images of indicia disposed on a mirror-like substrate, the apparatus comprising:
 - a plurality of illumination elements for providing incident light rays so as to illuminate the mirror-like substrate, thereby producing reflected light rays;
 - an image sensor; and
 - a selector/converger that selects a bundle of the reflected light rays having an elongated cross-section, and converges the bundle of the reflected light rays upon the image sensor so as to form an image of at least a portion of the indicia on the image sensor.

2. The apparatus of claim 1, wherein the selector/converger comprises:
- an elongated slot aperture having a longitudinal axis for selecting a bundle of the rays reflected by the mirror-like substrate to provide a selected ray bundle having an elongated cross section; and
 - a lens, cooperative with the elongated slot aperture, for converging the selected ray bundle so as to provide a substantially focused image of the indicia on the image sensor, and to provide an image of the illumination elements on the image sensor that is both substantially defocused along the longitudinal axis, and substantially focused transverse to the longitudinal axis.
3. The apparatus of claim 1, wherein the selector/converger comprises:
- an elongated mirror having a longitudinal axis for selecting a portion of the rays reflected by the mirror-like substrate so as to provide a reflected selected ray bundle having an elongated cross section; and
 - a lens, cooperative with the elongated mirror, that converges the selected ray bundle so as to provide a substantially focused image of the indicia on the imaging device, and to provide an image of the illumination elements on the imaging device that is both substantially defocused along the longitudinal axis and substantially focused transverse to the longitudinal axis.
4. The apparatus of claim 1, wherein the selector/converger comprises:
- an elongated curved mirror having a longitudinal axis for selecting and converging a portion of the rays reflected by the mirror-like substrate so as to provide a substantially focused image of the indicia on the imaging device, and so as to provide an image of the illumination elements on the imaging device that is both substantially defocused along the longitudinal axis, and substantially focused transverse to the longitudinal axis.
5. The apparatus of claim 1, wherein the plurality of illumination elements includes a subset of illumination elements that are disposed with respect to the selector/converger so as to provide dark-field illumination of the indicia.
6. The apparatus of claim 1, wherein the plurality of illumination elements includes a subset of illumination elements that are disposed with respect to the selector/converger so as to provide high-angle darkfield illumination of the indicia.
7. The apparatus of claim 1, wherein the plurality of illumination elements includes a subset of illumination elements that are disposed with respect to the selector/converger so as to provide bright-field illumination of the indicia.
8. The apparatus of claim 1, wherein the plurality of illumination elements is mounted on a printed circuit board, and the selector/converger includes an elongated slot in the printed circuit board, and a lens system, the elongated slot being disposed in front of the lens system so as to function as an aperture stop.
9. The apparatus of claim 1, wherein the plurality of illumination elements includes a diffuser disposed between a subset of the illumination elements and the mirror-like substrate so as to provide diffused and distributed light suitable for brightfield illumination of the indicia.
10. An apparatus for forming images of indicia disposed on a mirror-like substrate, the apparatus comprising:
- a plurality of illumination elements for providing incident light rays so as to illuminate the mirror-like substrate, thereby producing reflected light rays;

- an image sensor; and
 - a lens/aperture system including an elongated aperture slot having a longitudinal axis, the lens/aperture system being characterized by a first depth of field for focusing upon the image sensor along a longitudinal direction, the first depth of field being substantially smaller than a second depth of field for focusing upon the image sensor along a transverse direction.
11. The apparatus of claim 10, wherein a virtual image of the plurality of illumination elements is not disposed within the first depth of-field and is disposed within the second depth of field.
12. The apparatus of claim 10, wherein the indicia on the mirror-like substrate is disposed both within the first depth of-field and within the second depth of field.
13. The apparatus of claim 10, wherein a virtual image of the plurality of illumination elements is not disposed within the first depth of-field and is disposed within the second depth of field, and wherein the indicia on the mirror-like substrate is disposed within both the first depth of-field and the second depth of field.
14. The apparatus of claim 10, wherein the plurality of illumination elements is disposed on a printed circuit board, and the printed circuit board includes an elongated aperture stop cooperative with a lens system of the lens/aperture system.
15. The apparatus of claim 10, wherein the plurality of illumination elements is disposed on a printed circuit board, the printed circuit board includes an elongated aperture stop cooperative with a lens system of the lens/aperture system, and the elongated aperture slot is disposed so as to provide the only paths through the lens system.
16. The apparatus of claim 14, wherein the printed circuit board is opaque.
17. The apparatus of claim 10, wherein the lens/aperture system includes a pair of baffles for defining an elongated aperture cooperative with a lens system of the lens/aperture system.
18. The apparatus of claim 10, wherein the plurality of illumination elements provides incident light rays via a half mirror so as to illuminate the mirror-like substrate.
19. The apparatus of claim 10, wherein the plurality of illumination elements includes a first plurality of darkfield illumination elements and a second plurality of darkfield illumination elements, and the apparatus further comprises:
- means for alternately energizing the first plurality of darkfield illumination elements and the second plurality of darkfield illumination elements;
 - first memory means, cooperative with the image sensor, for storing a first darkfield image resulting from energizing the first plurality of illumination elements;
 - second memory means, cooperative with the image sensor, for storing a second darkfield image resulting from energizing the second plurality of illumination elements;
 - image combination means, cooperative with the first and second memory means, for combining the first darkfield image and the second darkfield image so as to provide an extended darkfield image.
20. The apparatus of claim 19, wherein the elongated aperture slot is rotatable.
21. The apparatus of claim 19, wherein the elongated slot aperture can assume a plurality of quantized angular orientations.
22. The apparatus of claim 19, wherein the elongated slot aperture is formed by a liquid crystal shutter.

23. The apparatus of claim 19, wherein the image combination means includes means for performing a per-pixel comparison of the first darkfield image and the second darkfield image, so as to provide an extended darkfield image, each pixel of the extended darkfield image being the darker pixel of a pixel of the first darkfield image and a corresponding pixel of the second darkfield image.

24. The apparatus of claim 10, further including a mirror, cooperative with the lens/aperture system, for folding the optical path traversed by both the incident light rays and the reflected light rays.

25. An image formation apparatus for acquiring images of indicia on a mirror-like substrate, the apparatus comprising:

a plurality of illumination elements for providing incident light rays so as to illuminate the mirror-like substrate, thereby producing reflected light rays;

a printed circuit board for supporting and energizing the plurality of illumination elements, the printed circuit board including an elongated slot aperture having a longitudinal axis for selecting a bundle of the rays reflected by the mirror-like substrate to provide a selected ray bundle having an elongated cross section;

an image sensor; and

a lens, cooperative with the elongated slot aperture, for converging the selected ray bundle so as to provide a substantially focused image of the indicia on the image sensor, and to provide an image of the illumination elements on the image sensor that is both substantially defocused along the longitudinal axis, and substantially focused transverse to the longitudinal axis.

26. The apparatus of claim 25, wherein the plurality of illumination elements includes a subset of illumination elements that are disposed on the printed circuit board with respect to the elongated slot aperture so as to provide dark-field illumination of the indicia.

27. The apparatus of claim 25, wherein the plurality of illumination elements includes a subset of illumination elements that are disposed on the printed circuit board with respect to the elongated slot aperture so as to provide high-angle darkfield illumination of the indicia.

28. The apparatus of claim 25, wherein the plurality of illumination elements includes a subset of illumination elements that are disposed on the printed circuit board with respect to the elongated slot so as to provide brightfield illumination of the indicia.

29. The apparatus of claim 25, wherein the plurality of illumination elements includes a diffuser for diffusing the light provided by a subset of the illumination elements so as to provide brightfield illumination of the indicia.

30. The apparatus of claim 25, wherein the lens is characterized by an elongated clear aperture.

31. The apparatus of claim 25, wherein the lens is characterized by an elongated clear aperture, and the lens is mounted on the printed circuit board so as to be cooperative with the elongated slot aperture.

32. The apparatus of claim 25, wherein the elongated slot aperture is rotatable.

33. The apparatus of claim 25, wherein the elongated slot aperture can assume a plurality of quantized angular orientations.

34. The apparatus of claim 25, wherein the elongated slot aperture is formed by a liquid crystal shutter.

35. The apparatus of claim 25, further including:

at least one additional elongated slot aperture;

for each elongated slot aperture, a light blocker cooperative with the elongated slot aperture, for preventing light from traversing the elongated slot aperture.

36. The apparatus of claim 35, further including an all-but-one excluder, cooperative with each light blocker, for ensuring that light can traverse only one elongated slot aperture at a time.

37. An image formation apparatus for acquiring images of indicia on a mirror-like substrate, the apparatus comprising:

a longitudinally extended light source for providing incident light rays along the light source so as to illuminate a longitudinally extended portion of the mirror-like substrate, thereby producing reflected light rays;

an image sensor; and

a selector/converger that selects a bundle of the reflected light rays having an elongated cross-section, and converges the bundle of the reflected light rays upon the image sensor so as to form an image of at least a portion of the indicia on the image sensor.

38. An apparatus for forming images of indicia disposed on a mirror-like substrate, the apparatus comprising:

a plurality of illumination elements for providing incident light rays so as to illuminate the mirror-like substrate, thereby producing reflected light rays, the plurality of illumination elements including a first plurality of darkfield illumination elements and a second plurality of darkfield illumination elements;

an image sensor;

a selector/converger that selects a bundle of the reflected light rays having an elongated cross-section, and converges the bundle of the reflected light rays upon the image sensor so as to form an image of at least a portion of the indicia on the image sensor;

means for alternately energizing the first plurality of darkfield illumination elements and the second plurality of darkfield illumination elements;

first memory means, cooperative with the image sensor, for storing a first darkfield image resulting from energizing the first plurality of illumination elements;

second memory means, cooperative with the image sensor, for storing a second darkfield image resulting from energizing the second plurality of illumination elements; and

image combination means, cooperative with the first and second memory means, for combining the first darkfield image and the second darkfield image so as to provide an extended darkfield image.